Ambient air quality impacts of a coal-fired power station in Lephalale area

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A research report submitted to the Faculty of Science

for the degree of Master of Science

September 2013

Declaration

I declare that this research report is my own unaided work. It is submitted in partial fulfilment of the requirements for the degree of Master of Science in the School of Geography, Archaeology and Environmental Studies at the University of Witwatersrand, Johannesburg. It has not been submitted previously for any degree or examination at any other University.

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(Mavhungu Sydney Muthige)

_____day of_____2013

This research is dedicated to my parents

Mr Muyanalo Ewert Muthige and Mrs Ndivhudzannyi Eunice Muthige

Abstract

Lephalale Municipality is a predominantly rural Municipality with 38 villages, two townships (Marapong and Onverwacht) and one town, Lephalale. Lephalale, formerly known as Ellisras, is a town situated in the "heart of the Bushveld" in Limpopo province. The town is growing rapidly and more industries are becoming concentrated within this small town. The construction of Medupi power station which is underway and other projects such as the expansion of Grootegeluk mine (coal 3 and 4 projects), and road developments in the area; have led to concern about the ambient air quality of the area. Other possible future projects are the Coal to Liquid project by Sasol and the Coal Bed Methane project by Anglo American Thermal Coal. The purpose of this study is to determine the ambient air quality impact of the Matimba power station in the Lephalale area. The AERMOD model and ambient air quality data obtained from Eskom's Grootstryd and Marapong monitoring stations were used to assess the ambient air quality of Lephalale. Sulphur dioxide and Nitrogen oxides were investigated. Both the model's results and the ambient air quality monitoring data indicated that the power station contributes to high -ground level concentrations of Sulphur dioxide. AERMOD simulated the nitrogen oxides results as nitrogen dioxide. From the study it is concluded that the power station is not the only source of nitrogen oxides. Nitrogen oxides concentrations were associated with low-level sources. The relationship between the criteria pollutants in this study was assessed. The study found that there is no relationship between sulphur dioxide and nitrogen oxides. This finding was used to support the idea that sulphur dioxide and nitrogen oxides are from different sources. It was also established that seasonality has an influence on the ground level concentrations of pollutants in the area.

Preface

Deterioration of air quality due to industries and power utilities is a global concern. Coal fired power plants significantly pollute the environment (Oman *et al*, 2002). South Africa relies heavily on coal for its electricity (Thambiran *et al*, 2007). The impact of power stations is due to their high energy requirements and different inputs and outputs in the plant. These effects on the environment are more significant when there is a mine in the vicinity of the power plant that supplies the coal. It is also the case in Lephalale area: the Grootegeluk coal mine serve as a feeder for both Matimba and Medupi (not yet in operation) power stations. The power stations emit a lot of criteria pollutants such as sulphur dioxide, nitrogen oxides, carbon monoxide and carbon dioxide (Shindell and Faluvegi, 2010).

In this dissertation, the deterioration of ambient air quality due to the Matimba power station in Lephalale area is assessed. Analysis of ambient air quality monitoring data from the period of 2005 till 2010 is done. AERMOD model is run for the period of 2010. Both the model and the monitoring data are used to evaluate the impacts caused by sulphur dioxide and nitrogen oxides in the area. The influence of seasons on ambient air quality is also investigated.

The dissertation consists of five chapters. **Chapter 1** outlines the background of the study, the objectives, the historical background on the air quality studies done in Lephalale, and the legislation governing air quality in South Africa. **Chapter 2** outlines the methodology used to collect the ambient air quality data collected from Grootstryd and Marapong monitoring station. The approach used to analyse the data is also discussed. **Chapter 3** provides an analysis of the ambient air quality data used. It gives an in-depth analysis of the impact of the power station in the area. The baseline condition of the study area is established and the results are displayed in terms of scatter plots, linear regression models, and diurnal variations of the pollutants. **Chapter 4** provides a discussion of the model results. **Chapter 5** summarises and concludes the research findings.

The author wishes to express his sincere gratitude to the following individuals and organisations for their assistance and contributions:

- My family for their endless support and encouragement during the course of the study. If it was not for their faith in me and constant words of encouragement I would not have managed to finish this dissertation.

- My co-supervisor Mr Roelof Burger for his guidance on formatting, the use of Qgis and constant supervision of this entire dissertation.
- My supervisor Prof Stuart Piketh for his supervision, insight on analysing monitoring data and financial assistance during the course of the study.
- The following Eskom Corporate Service Division personnel:
    - Gerhard De Beer for providing me with ambient air quality monitoring data from Grootstryd and Marapong monitoring station as well as providing access to EDWEIS to analyse the air quality data.
    - Gabi Mkhatshwa for providing me with all the Eskom internal reports used in this study.
    - Maluta Mbedzi for his support, words of encouragement and lectures on atmospheric pollution dispersion and dispersal of pollutants from tall stacks.
    - Jon Keir for assistance with the emission factors.
- Eskom for providing me with vacation work and financial support throughout the course of the study.
- My friends (Makondelela Sandane, Khuthadzo Ndwambi, Samuel Madzivha, Avhasei Mudau, Crystal Baloyi, Mafuza Maya, Rugare Zhou, Rofhiwa Ratshilumela and Mulalo Tshamano) for their support throughout the course of the study.
- The words of advice and motivation from Mr Thandizwa Ntsimbi are highly appreciated.

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Nomenclature

ADMS	Atmospheric Dispersion Modelling System
AERMOD	American Meteorological Society/Environmental Protection Agency Regulatory Model
APPA	Atmospheric Pollution Prevention Act
AQA	Air Quality Act
CALPUFF	Californian Puff Model
CRG	Climatology Research Group
DEAT	Department of Environmental Affairs and Tourism
Fe	Iron
FeS_2	Pyrite
FPM	Fine particulate matter
HCN	Hydrocyanic Acid
HO_2	Hyrdroperoxyl radical
$HOSO_2$	Hydroxysulfonyl radical
H_2S	Hydrogen sulphide
H_2SO_4	Sulphuric acid
ISCST3	Industrial Source Complex Short Term3
N	Nitrogen
NH_3	Ammonia
NO	Nitric oxide
NO_2	Nitrogen dioxide
N_2O	Nitrous oxide
O	Oxygen
O_3	Ozone
OH^-	Hydroxide
PBL	Planetary Boundary Layer

S	Sulphur
SANAS	South African National Accreditation System
SAWS	South African Weather Services
SO_2	Sulphur dioxide
SO_3	Sulphur trioxide
SO_4^{2-}	Sulphate
SRTM	Shuttle Radar Topography Mission
USEPA	United States Protection Agency
VOC	Volatile Organic Compounds

Chapter 1: Overview

Chapter one gives an outline of sources of pollutants in Lephalale with the power station being the main focus. The criteria pollutants, sulphur dioxide and nitrogen oxides' characteristics are discussed. Pollution dispersal within the atmosphere and pollution dispersion modelling are also covered in this chapter.

Introduction

Lephalale area is located in the Limpopo province within the Waterberg District municipality in South Africa. It is known for its rich deposits of coal. It is one of the fastest growing towns in Limpopo and is becoming a developmental hub. The already existing industrial activities are coal mining and other related activities as well as power-station-operations by Eskom and Sasol's petrochemical operations. Lephalale is also a home to townships such as Marapong and Onverwacht and other informal settlements using coal, paraffin and wood as a fuel source. Other sources of concern to air quality are the brickworks operations, agricultural activities, biomass burning, vehicles and other fugitive dust emissions.

There are many developmental activities that take place within the area. There is the construction of Medupi power station which is underway, the expansion (coal 3 and coal 4 project) of the Grootegeluk mine, and the road developments in the area. Some of the possible future projects are: the Coal to Liquid project by Sasol, the Coal Bed Methane Project by Anglo American Thermal Coal and other exploration activities. There is also a possibility of two more power stations from the coal 3 and Coal 4 project.

Various air quality studies associated with the Matimba power station in Lephalale have been undertaken by Eskom for the past 30 years. The most important of these studies are the continuous ambient air quality monitoring before the commissioning of the Matimba power station in the area, a pollution dispersion model database conducted by Turner (1993) and an air quality evaluation of wet deposition around the power station (Rorich, 2004).

In 2009, a study was conducted to specifically address the air quality issues within the whole Waterberg district (Walton and Ngcukana, 2009). The output of the study was an air quality management plan for the district. In 2012, the whole of the Waterberg district and the Bojanalo district municipality in the North West province were declared a national air quality priority area known as Waterberg-Bojanalo Priority Area.

Objectives of the study

A part of the challenges of studying the impact of a source on air quality is to be able to isolate the impact of the source. In the Highveld, for example, this kind of study is complicated by the presence of abroad variety of sources of air pollution in the area such as Sasol Secunda, coal mining and various metallurgical plants. Studying the impact of the Matimba power station in the Lephalale area is made easier by the fact that the Matimba power station is currently the only high emission source in Lephalale. Source multiplicity with respect to tall stack emissions will be eliminated, making it ideal to investigate the ambient air quality impact on the area.

The objectives of the study are to:

- Evaluate the impact of the Matimba power station on the ambient air quality of Lephalale.
- Determine the influence of seasonal and diurnal variation on ambient air quality of Lephalale.
- Evaluate the compliance of air quality pollutants based on local limits.
- Evaluate the significance of sulphur dioxide and nitrogen oxides sources in the area.

Literature review

Components influencing air quality

Sulphur dioxide

When coal is burned, about 95 % of sulphur is released as sulphur dioxide (SO_2) (Franco and Diaz, 2009). If there is no Flue Gas Desulphurization technology in a coal-fired power station, the sulphur dioxide content enters into the atmosphere as it is, without any efforts of minimization. The larger the sizes of the power plant, the more pollutants are released into the atmosphere (Hewit, 2001). Sulphur in coal is formed as a result of impurities within the coal itself: mostly from pyrite (FeS_2) (Tzimas *et al*, 2007). It is mostly found as sulphides, organic sulphur compounds, trace elements of sulphur and sulphates. The concentration of sulphur in coal is mainly controlled by the coal age and the location of the coal resource. During coal combustion the sulphur contained in coal is released in a gaseous state. Coal is

highly associated with mineralization of Iron oxide of sulphur known as pyrite, which can be oxidized as follows (Fleig *et al*, 2009):

$2FeS(s) \rightarrow 2FeS(s) + S_2(g)$……... (1)

$2FeS \rightarrow 2Fe + S_2$ ……... (2)

$S_2 + 2O_2 \rightarrow 2SO_2$…….. (3)

SO_2 is only formed in high temperatures and the presence of oxygen. Under low temperatures SO_2 can be further oxidized to SO_3 as indicated by the following reaction (Fleig *et al*, 2009):

$SO_2 + O \rightarrow SO_3$…….…….. (4)

$SO_2 + OH \rightarrow HOSO_2$……. (5)

$HOSO_2 + O_2 \rightarrow SO_3 + HO_2$……. (6)

Within the atmosphere, primary pollutants are converted to secondary pollutants (Hewitt, 2000). Atmospheric sulphur dioxide is converted into sulphate (equation 7) and its life span depends on the oxidation rate (Khoder, 2002).

$SO_2 + O \rightarrow SO_3$ ……..…… (7)

$SO_2 + OH^- \rightarrow SO_3 + H$ …… (8)

$SO_2 + H_2O_2 \rightarrow H_2SO_4$ ……..…… …….. (9)

Anthropogenic emissions of sulphur dioxide are found in both aqueous and gaseous states in the atmosphere (Mphepya *et al*, 2004). It is then converted into sulphuric acid (equation 9). During precipitation, the acids impact on the ecosystem, especially when the soils are not basic enough to buffer the acidity of the precipitation (McGonigle *et al*, 2004). Poor dispersal of pollutants in the atmosphere leads to formation of fog as a result of the oxidation of sulphur dioxide and sulphur trioxide (SO_3) (Lenchev *et al*, 2008).

Nitrogen oxides

The most significant producers of nitrogen oxides (NO_x) are power generation and automobiles (Zhou *et al*, 2011). NO_x emissions from power stations are formed under high combustion temperatures (Ma, 2010). NO_x plays a significant role in the formation of acid rain, smog and ground-level ozone by chemically reacting with water vapour, sunlight and

Volatile Organic Compounds (VOC's) (Richter *et al*, 2005, Fan *et al*, 2010). Nitric acid is formed through the oxidation of NO_x and it results into the formation of particulates that cause reduced visibility and respiratory diseases (Kim *et al*, 2009). Nitric acid reduces biodiversity and decreases the productivity of the ecosystem. NO_2 affects the net radiation of the sun.

The process of nitrogen oxides ($NO + NO_2$) formation is complex (Ma, 2010). It involves a lot of species with the most important being NO, NO_2, N_2O, NH_3 and HCN. NO normally amounts to at least 90 % of the NO_x produced (Bris *et al*, 2007). The particle size and moisture content of the coal affect the amount of NO_x that is produced (Hill and Smoot, 2000). The particle size of the coal determines devolatisation of coal and nitrogen in relation to peak temperatures and the rate of the increase in temperatures. Small particles experience rapid heat up and these results in a high level of devolatisation and the formation of a large amount of NO_x. Coals with high moisture content have higher NO_x emissions (Hill and Smoot, 2000). NO_x formation declines with the increase of coal swirl.

The amount of NO in coal flame from prompt NO_x is negligible (Bris *et al*, 2007). The amount of NO generated by thermal mechanism is directly proportional to the temperature. It is formed when nitrogen within the atmosphere reacts with oxygen in the air at high temperatures (Diaz *et al*, 2008). The process is governed by the following reactions (Hill and Smoot, 2000):

$O + N_2 \leftrightarrow NO + N$…… (10)

$N + O_2 \leftrightarrow NO + O$…… (11)

$N + OH \leftrightarrow NO + H$…….. (12)

Equation 12, of the thermal mechanism takes into account the effect of oxygen and hydrogen radicals on nitrogen oxide formation (Hill and Smoot, 2000). The thermal formation of NO takes place within a few seconds and depends on residence time and atomic oxygen concentration (Benoit *et al*, 2011). Fuel NO_x is formed when the nitrogen in the coal is oxidised (Diaz *et al*, 2008). The nitrogen being oxidised is found either in volatile matter or char. The volatile NO is formed from the volatiles leaving the coal during devolatisation and char NO is formed from the particles that remain on the coal before it is oxidised (Bris *et al*, 2007). Both the HCN and NH_3 species are formed when fuel nitrogen leaves the coal particles. Fuel NO is more readily formed than in thermal mechanism because it has a weaker

bond between N-H and N-C than the triple molecular bond in thermal mechanism. They are both converted into N_2 or NO as the end product (Diaz *et al*, 2008).

Dispersion potential of pollutants in the atmosphere

The atmosphere is never calm: it is always in motion at varying scales (Tyson and Preston-Whyte, 2000). The meteorological parameters responsible for the atmospheric dispersion of pollutants are complex in nature: the end result is the complexity of the dispersion of pollutants (Indumati *et al*, 2009). The pollutants in the atmosphere are transported via two processes i.e. vertical and horizontal transportation. Vertical transportation is controlled by the atmosphere's stability structure whereas the horizontal transportation is controlled by the local thermo-topographic winds near the surface and the large-scale circulation in changing synoptic fields (Tyson and Preston-Whyte, 2000).

Within South Africa, the atmospheric circulation is characterized by anti-cyclonic circulation throughout the year (Figure 1.1). This is due to the dominance of the continental high pressure cell in the interior, the South Atlantic high pressure cell in the western coast and the South Indian high pressure cell in the east coast. This anti-cyclonic circulation occurs mostly in the interior with an average of 800hpa geospatial height level. The stability and depth of these semi-permanent anti-cyclone circulations lead to the formation of the South African layer. The haze layer covers most parts of South Africa during the dry seasons (Piketh *et al*, 1999). In South Africa, 75% of the aerosols are transported to the Indian Ocean (Piketh *et al*, 1999).

Recirculation and transport of aerosols and trace gases in South Africa is largely controlled by the position of the anticyclones. The transportation system of aerosols in South Africa is largely influenced by the Semi-permanent South anticyclone, the continental anticyclone and the South Indian anticyclone. The position of the downward limb of the Walker circulation, the easterly waves of the Southern Africa subcontinent and the westerly waves in the mid-latitudes all play a role in the transportation of trace gases and aerosols (Garsteng, *et al*, 1996).

The large-scale anti-cyclonic activities that take place over the Southern African region result into subsidence inversion in South Africa. Prolonged periods of anti-cyclonic weather during winter seasons in South Africa over the plateau result in subsidence inversion which lasts for longer periods. Such subsidence inversion - characterised by little diurnal variation and fairly

constant afternoon mixing depth - reduce the dispersion of pollutants in the atmosphere over the plateau.

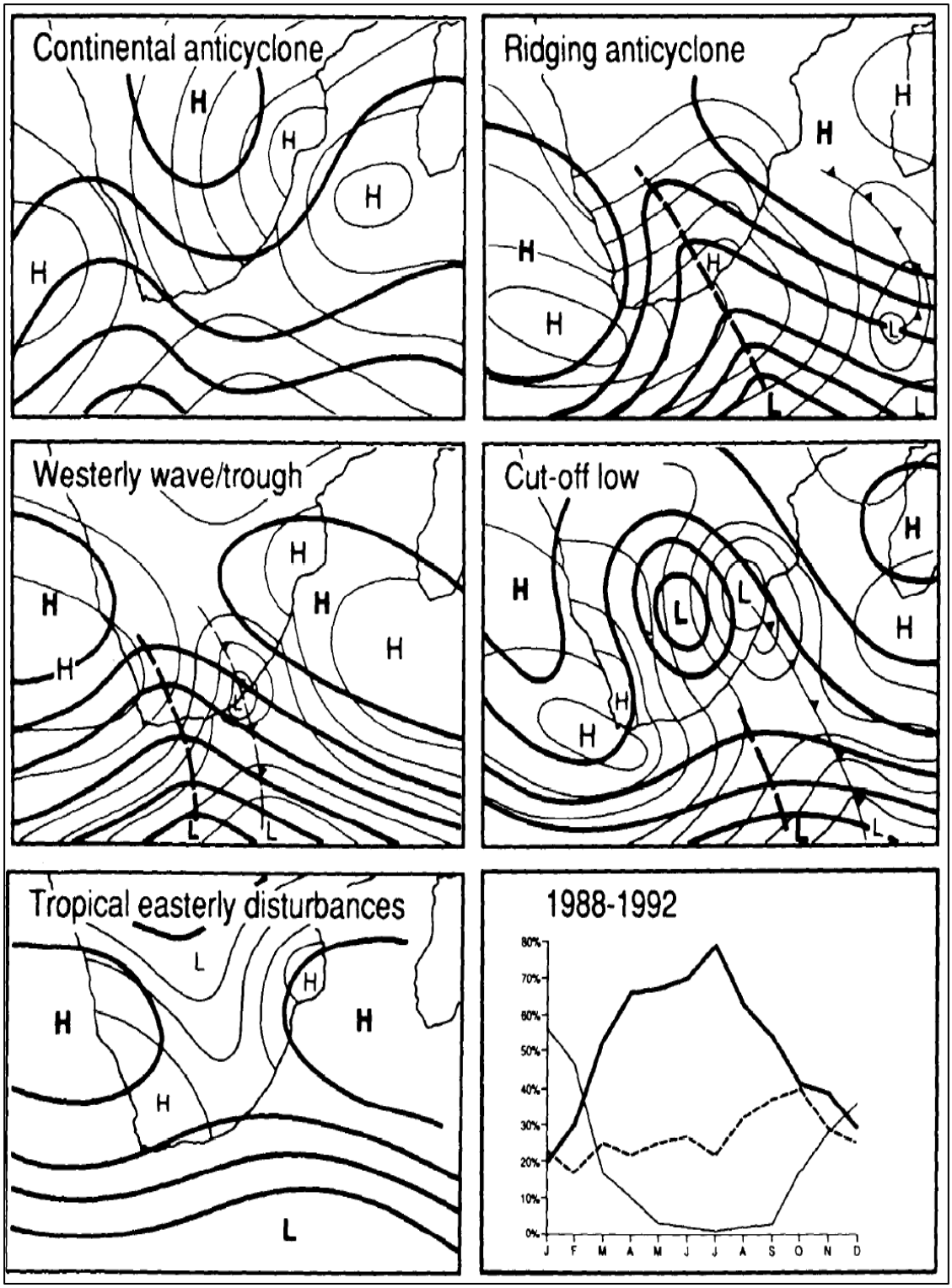

Figure 1. 1 Dominant synoptic circulation types in Southern Africa and their frequency of occurrence from 1988-1992 (after Preston-Whyte and Tyson, 1988)

Emissions in South Africa travel in large air masses with the probability of recirculating over land for a period of a week and above. The recirculation of masses of air is profound within the stable layers of South Africa, within 500 hpa and 800 hpa. The stability of the area improves the ability of emissions to mix (Horizontal diffusion) with each other and form stratified layers (Piketh *et al*, 1999). The stable layers prolong residence days and inhibit vertical exchanges in the atmosphere but promote horizontal diffusion of emissions (Tyson *et al*, 1996).

Dispersion of pollutants from tall stacks

Eskom and the other major industrial facilities on the Highveld have implemented a tall stack policy on their operations (Khumalo, 2002). The use of tall stacks has been considered to be advantageous in that it reduces the level of ground level concentrations (Hale, 1976). The distribution of wide spread effluents, which is influenced by tall stacks, allows for high emission rates, since the ground level concentrations will be reduced. This allows the emitters pollutants to meet ambient air quality standards.

The use of tall stacks influences the quantity and spread of atmospheric pollutants in the atmosphere. By emitting pollutants at higher levels in the atmospheres, the transport and dispersal of pollutants is altered (Hale, 1976).

The design of the stacks within Eskom's property is such that they should generally be above the developing surface inversion layer that forms during the night: reaching its highest intensity just before the sunrise (Tosen and Pearse, 1987). Under such specific conditions, tall stacks' emissions are trapped between the top of the surface inversion and the bottom of a semi-permanent subsidence inversion or absolutely stable layer, typically located between 1500m and 3000m (Annergarn *et al*, 1996; Turner, 2001). Just after the sunrise, the surface inversion is systematically eroded away from the bottom as the ground is heated by the incoming solar radiation. Typically, the surface inversion is expected to be completely eroded between 9:00 and 10:00. Then the mixing depth increases through convective heating to the bottom of the lowest subsidence inversion or absolutely stable layer. Emissions from tall stacks are then mixed towards the ground and the end result is that pollution levels increase steadily until the pollutants are mixed well through the entire layer.

Ground level concentrations are generally expected to start rising just after sunrise at about 06:00, reach a peak at about 12:00, and then fall off to the background level just after sunset, 18:00 (Annergarn *et al*, 1996).

Dispersion of pollutants from low-level sources

Pollutants arising from low-level sources are subjected to control by surface inversions (Annergan *et al*, 1996). Emissions from domestic fuel burning, short stacks, fugitive dust and motor vehicle emissions are trapped below the inversion layer at night.

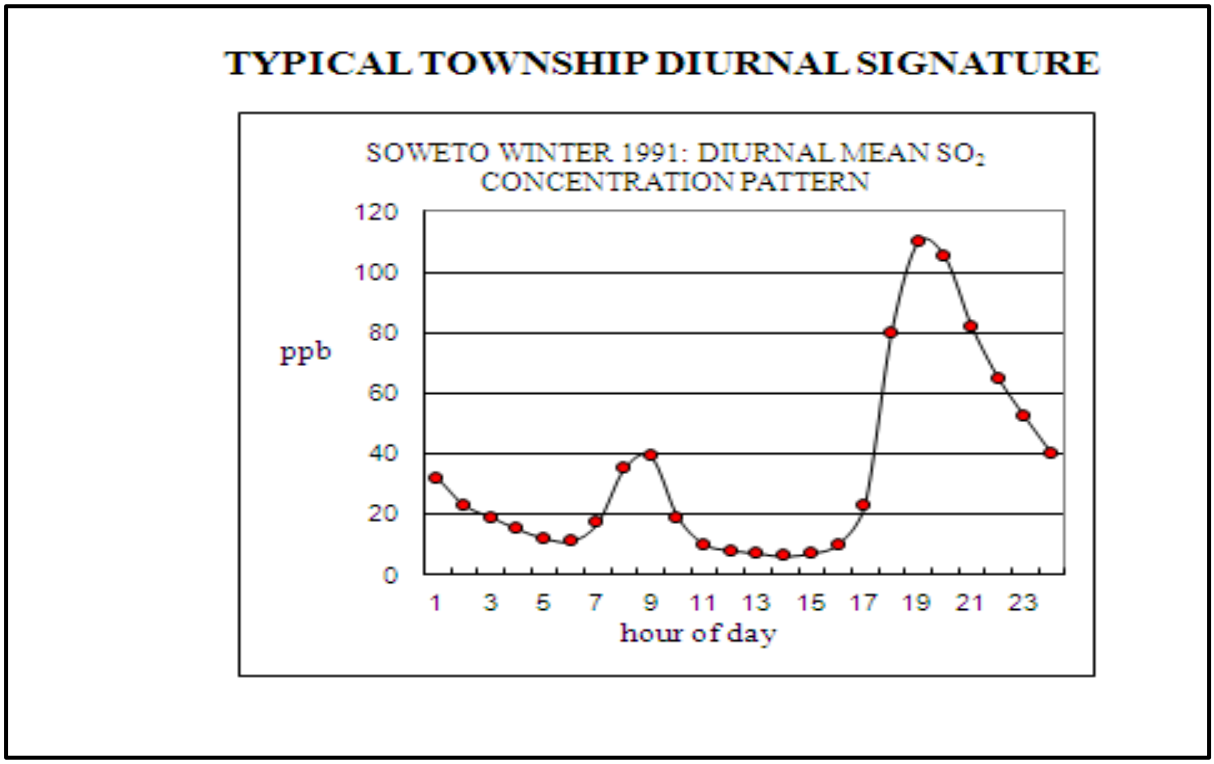

Figure 1. 2 Typical low-level sources diurnal signature (Turner, 2006)

Emissions from low-level sources emitted during the evening are dispersed poorly in the stable boundary layer and the end result is the elevated ground level concentrations near the source (Turner, 1996). The signature given by low-level sources is different from the one from tall stacks. In most cases it shows a bimodal distribution with higher peaks recorded in the evening and the early morning (Figure 1.2). The early morning peaks indicate that the inversion layer has not yet been eroded due to lack of sunlight.

Planetary Boundary Layer

The Planetary Boundary layer (PBL) is defined as the lowest region of the atmosphere (1-2 km). It is influenced by its contact with the earth surface through momentum exchange, heat transfer and water vapour (Kaimal and Finnigan, 2004). The growth of PBL is controlled by variation in flux of heat and water which are affected by roughness of surface and albedo (Garcia-Carreras *et al*, 2010). When numerical models are made for PBL, the time scale used

is an hour and the spacing is a few kilometres. The Planetary Boundary Layer has different layers i.e. the Convective Planetary Boundary Layer and the Stable Planetary Boundary Layer. Turbulence within the PBL is dominated by two forces i.e. wind shear and buoyancy. Buoyancy has higher control on the Convective Boundary layer whereas wind shear dominates the Stable Boundary Layer.

Aerosols and moisture content mix in the Convective Boundary Layer and result in high concentrations in the mixed layer close to the clean and dry troposphere (Cohn and Angevine, 2000). Different flow patterns in the PBL manifest as a result of the dominating force. Studies have found that in the neutral case, eddies -which are identified by the downstream velocities - are elongated near the surface whereas in the convective case, eddies have no specific horizontal orientation (Moeng and Sullivan, 1994).

Diurnal cycles also occur on the PBL. It usually occurs during clear and calm days. When the net surface heat flux is directed upward after sunrise, it leads to the formation of daytime PBL. As more solar energy is absorbed by the earth's surface, free convective eddies become active in transporting sensible heat (moisture) upward to warm (moisten) the air above and momentum downward to accelerate the flow below (Zhang and Zheng, 2004). The rising eddies mix heat moisture and kinetic energy with their environment and this result into a counter gradient heat transfer known as entrainment. Rapid loss of heat in the late afternoon at the ground leads to new inversion. As a result, horizontal winds above the surface layer decouple from the surface friction. This leads to the formation of nocturnal low-level jet near to the top of the nocturnal inversion layer (Zhang and Zheng, 2004).

The mixing and dispersion of pollutants in the atmosphere within the Planetary Boundary Layer occurs by means of convection and turbulence (Boyouk *et al*, 2010). There is competition between mixing and chemical transformation in the changing of the atmospheric concentration. Chemical transformation, diffusion and transportation of pollutants in the Planetary Boundary layer are also controlled by the meteorological processes (Rao *et al*, 2003)

Atmospheric characteristics and Stability

The depth of surface mixing and the stability of the atmosphere play a fundamental role in pollution dispersal in the atmosphere. Pollution dispersal occurs both vertically and horizontally. Atmospheric stability is often referred to as the extent to which the vertical

motion can take place or the degree of turbulences. Atmospheric stability affects the vertical dispersion of pollutants and therefore also indirectly affects the horizontal movement of winds (Pasquill and Smith, 1983; Oke, 1990).

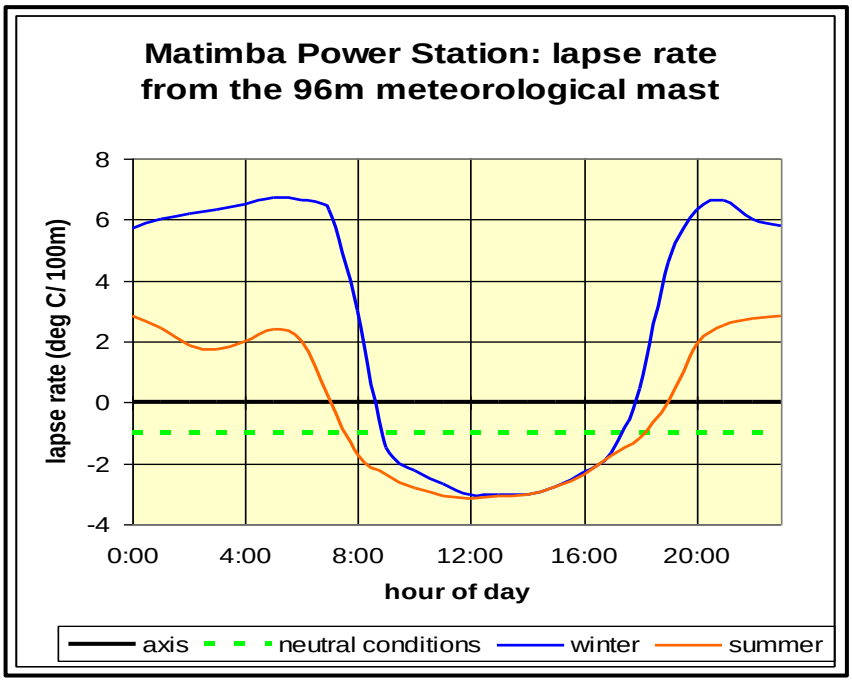

Figure 1. 3 Seasonal mean diurnal lapse rate at Matimba power station (Turner, 1993)

The latitude and the elevation of the Waterberg and the Highveld area combined with the prevailing synoptic meteorology result in atmospheric dispersion with distinctive characteristics. The lower planetary boundary layer exhibits a unique diurnal stability pattern (Turner, 1993).

The stability pattern is the same throughout the year in Lephalale. The stable boundary layer is stronger and deeper at night during the winter compared to the summer (Figure 1.3). The state of the near planetary Highveld and Waterberg atmosphere swings between strong ground level temperature inversion during the night and substantial convective turbulence during the day. The neutral layer (Figure 1.3) is usually capped by an elevated inversion which is a result of cool air subsiding off the sub continental high pressure cell.

Atmospheric pollution dispersion modelling

Atmospheric dispersion modelling is used to determine the impact of air pollution sources in an area. An estimation of ground level concentrations of pollutants at a distance from the emission source is made during atmospheric modelling (Cora and Hung, 2003). It is also used

to predict the end location of pollutants released into the atmosphere (Chang and Hanna, 2004). Dispersion modelling relies heavily on the use of mathematical equations to determine the concentration of pollutants, atmospheric chemistry, the distance travelled by the pollutants and physical processes within the plume (Holmes and Morawska, 2006). The algorithms and equations used in modelling rely on atmospheric processes and empirical data (ADEQ, 2004).

Dispersion models allow the air quality specialist to make choices about the various air quality management options. These models are useful for the design and configuration of pollution sources so that ambient impacts can be minimised. Predictions of highest concentrations for regulatory purposes can also be made. Models used for regulatory purposes are designed to be conservative in nature in order to set national ambient standards.

Atmospheric pollution dispersion models can be used for various purposes. Their application can be summarised as follows (Moussiopoulos *et al,* 1996, Ministry of Environment, 2004):

- Regulatory purposes i.e. to assess compliance with air quality standards and guidelines.
- Public information/education i.e. to create a database to inform the public of the ambient air quality status of their area.
- Scientific research e.g. to gain an understanding of the complex nature of the pollutants in the atmosphere, identifying gaps and weakness within the air quality studies and finding innovative ways to simulate atmospheric processes.
- Enhancing the design of experiments i.e. to determine the wind trend and emission fields so that optimal sampling sites are identified.
- The interpolation of measurement stations i.e. calculations are made to determine concentration of pollutants between networks of monitoring stations.
- Aiding the interpretation of observations.
- Designing air quality management systems.
- Deciding where to locate new pollution sources to minimise pollution impact.
- Describing the sequence of processes e.g. hourly average of SO_2 concentrations from a power station.
- Delineation of buffer zones

Nowadays most models make use of computer based programs. They usually require input data such as the meteorological conditions of the area, background concentrations of pollutants and terrain data. The modelling process can be generically be summarised into data input, data processing, data output and data analysis (Figure 1.4). Atmospheric pollution dispersion models have various types. This study will focus on the Eulerian, Gaussian and Lagrangian models.

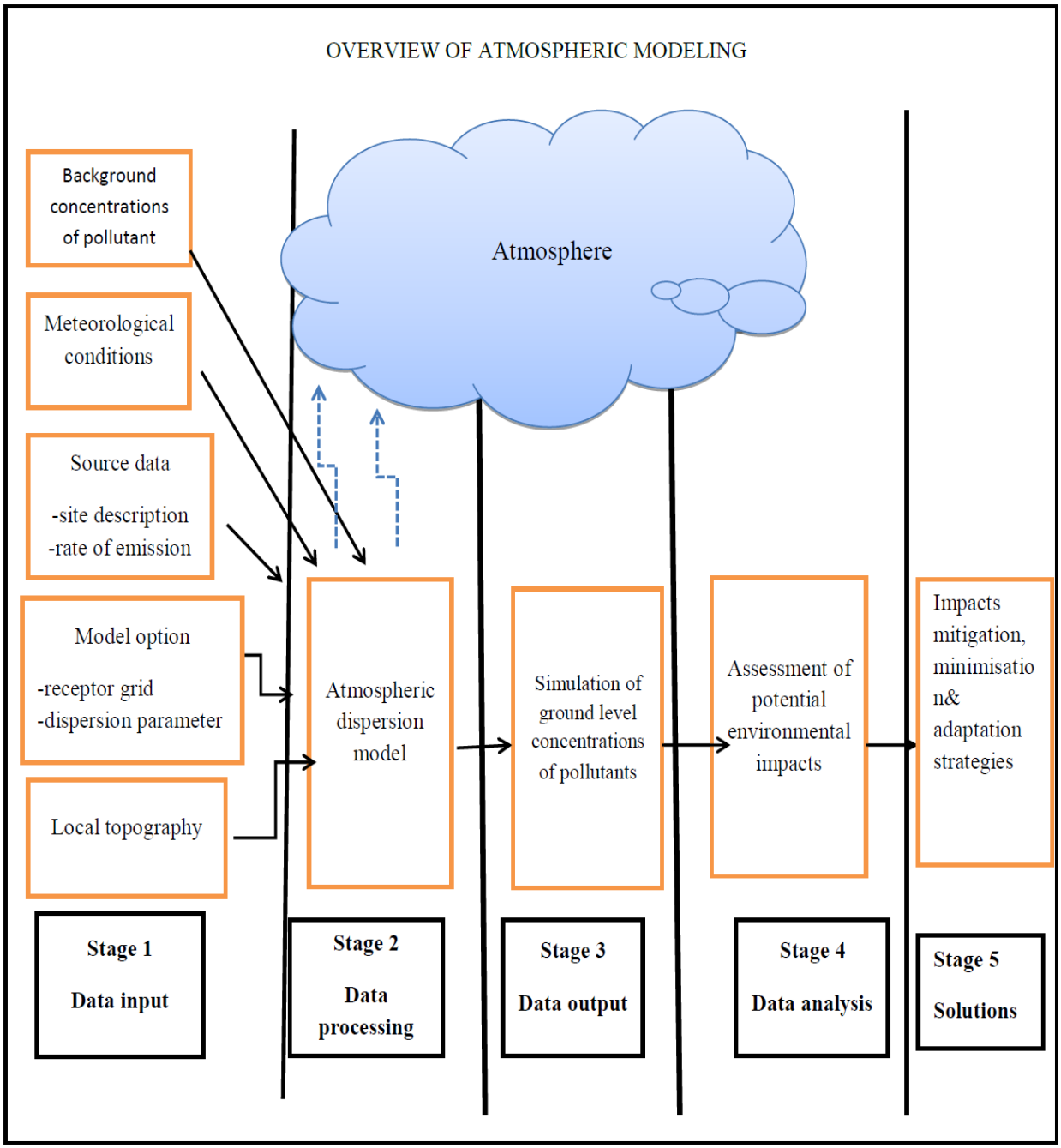

Figure 1. 4 Atmospheric modelling processes indicating all the necessary steps involved in pollution dispersion modelling (after Ministry of Environment, 2004)

Gaussian models

Gaussian models are used mainly for regulatory purposes (Holmes and Morawska, 2006). They are used in local scale studies. The Gaussian models are easy to use and are therefore widely used. They also require minimal computational space. Gaussian models are based on vertical and horizontal plume dispersions under normal distribution within steady-state conditions (Abdal-Rahman, 2008). The concentration of pollutants spread out from the centre of the plume (Figure 1.5). The models assume that the meteorological conditions are constant throughout the dispersion process from source to receptor (Ministry of Environment, 2004). The emissions and meteorological conditions change hourly. The hourly calculations of the model are independent from each other. Some of the Gaussian Dispersion models are ISCST3, Screen3 and AERMOD (Table 1.1). Only the AERMOD Dispersion model will be discussed within the methodology section.

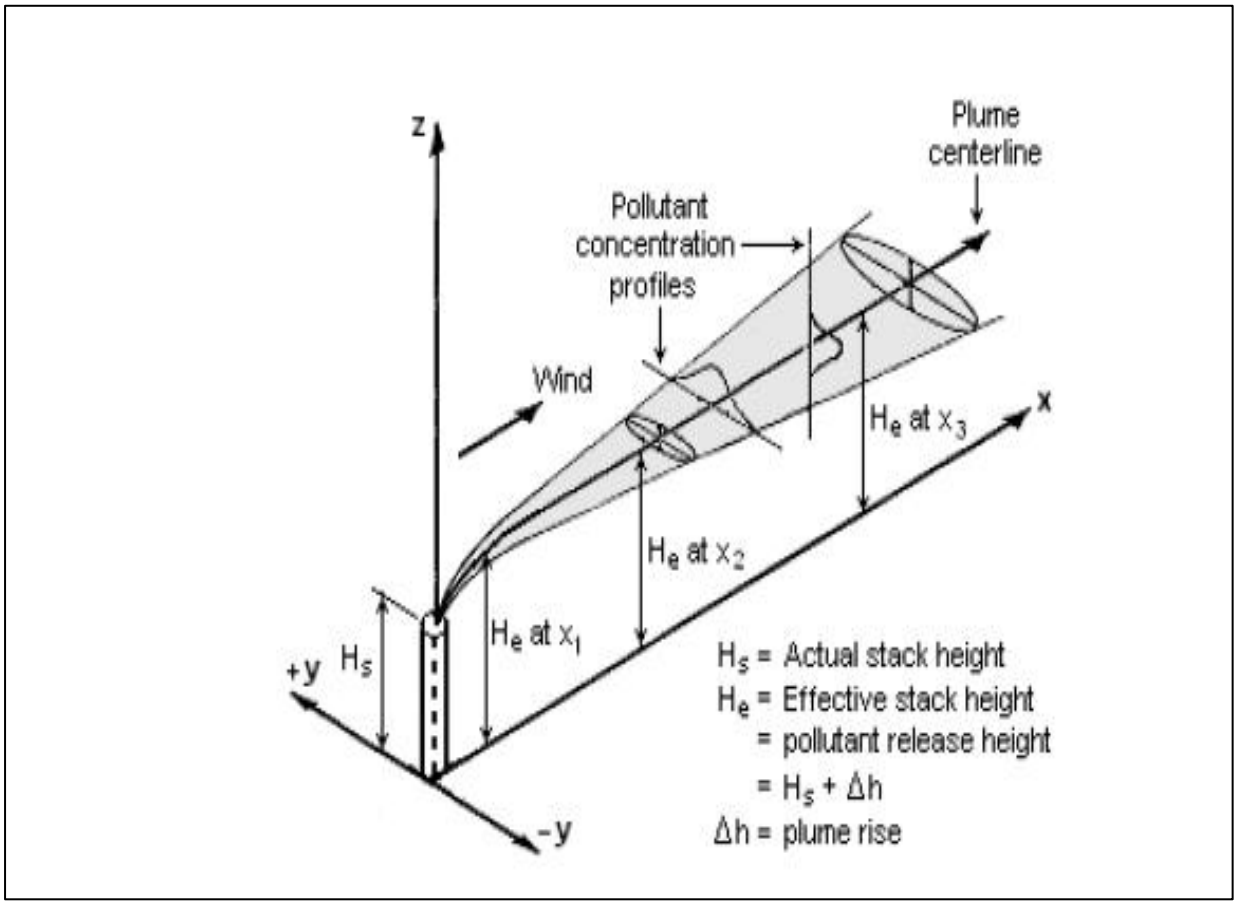

Figure 1. 5 Vertical and horizontal dispersion of pollutants from the centre line of the plume (Wayson *et al*, 2000)

Gaussian models assume that plume concentration at each downstream has its own independent concentration (Moussiopoulos *et al*, 1996). The concentration of the plume is calculated by the complete equation (below) for Gaussian dispersion modelling for continuous buoyant air plumes (Beychok, 2005).

$$\boldsymbol{C} = \frac{\boldsymbol{Q}}{\boldsymbol{u}} \cdot \frac{\mathfrak{f}}{\sigma_y \sqrt{2\pi}} \cdot \frac{\boldsymbol{\mathcal{G}1}+\boldsymbol{\mathcal{G}2}+\boldsymbol{\mathcal{G}3}}{\sigma\approx \sqrt{2\pi}}$$

Where:

$\mathfrak{f}$ = cross wind dispersion parameter

= exp $-y^2 / (2\sigma y^2)$

$\boldsymbol{\mathcal{G}}$ = vertical dispersion parameter = $\boldsymbol{\mathcal{G}1} + \boldsymbol{\mathcal{G}2} + \boldsymbol{\mathcal{G}3}$

$\boldsymbol{\mathcal{G}1}$ = vertical dispersion with no reflections

exp $- \mathcal{Z} - \mathcal{H})^2 \ 2\,\sigma_{\approx}^2 \ ]$

$\boldsymbol{\mathcal{G}2}$= vertical dispersion for reflection from the ground

exp $[- (\mathcal{Z} + \mathcal{H})^2 \ 2\sigma_{\approx}^2 \ ]$

$\boldsymbol{\mathcal{G}3}$= vertical dispersion for reflection from an inversion aloft

$\sum_{m=1}^{\infty}\{ \ exp\ [- \ Z - H - 2mL)^2 / \ 2\sigma_{\approx}^2)]$

$+ exp\ [- \ Z + H + 2mL)^2 / (2\sigma_{\approx}^2)]$

$+ exp\ [- \ Z + H - 2mL)^2 / (2\sigma_{\approx}^2)]$

$+ exp\ [\ (Z - H + 2mL)^2 / (2\sigma_{\approx}^2)]$

$\boldsymbol{C}$ = concentration of emissions, in g/m^3, at any receptor located:

X= meters downwind from the emission source point

Y= meters crosswind from the emission plume centreline

Z = meters above ground level

$\boldsymbol{Q}$= source pollutant emission rate, in g/s

$\boldsymbol{u}$= horizontal wind velocity along the plume centreline, m/s

$\boldsymbol{H}$ = height of emission plume centreline above ground level, in m

$\boldsymbol{\sigma z}$ = vertical standard deviation of the emission distribution, in m

$\boldsymbol{\sigma y}$ = horizontal standard deviation of the emission distribution, in m

$\boldsymbol{L}$ = height form ground level to bottom of the inversion aloft, in m

σz and σy are functions of the atmospheric stability class (i.e. a measure of the turbulence in the ambient atmosphere) and of the downwind distance to the receptor. The two most important variables that affect the degree of pollutant emission dispersion obtained are (a) the height of the emission source point and (b) the degree of atmospheric turbulence. Greater degree of pollutant dispersion is noticed when there is high turbulence.

Eulerian models

Eulerian models are applied widely in environmental analysis (Chang *et al,* 1998). Eulerian models define the model domain in terms of grid cells (Holmes and Morawska, 2006). They predict the transportation, dispersal and chemical transformation of pollutants within spatial gridded sources. The grid cells can either be two or three dimensional and they are fixed with respect to the earth's surface. The transportation, transformation and deposition of emissions are defined by mathematical algorithms in a fixed coordinate system (Jacobs, 1999). They are used for complex regional air quality problems because they make use of three-dimensional formulations. Atmospheric diffusion can be modelled by Eulerian models due to the use of numerical terms (DEAT, 2006).

Data sets used in Eulerian models are five dimensional. The grid cells within the modelling domain are three dimensional, i.e. x and y direction (horizontal) and the z direction (vertical). The remaining two are time and chemical species. The model output time is normally one hour.

Lagrangian models

Lagrangian models define an initial concentration of the plume within a region as a box and use mathematical algorithms to follow the movement of the plume within the atmosphere (Holmes and Morawska, 2006).

Table 1. 1 Comparison of pollution dispersal models according to functionality

Model	**Functionality**
CALPUFF	The Californian Puff Model is a multi-layered, non-steady-state Gaussian puff-dispersion model that is used to predict the effects of different meteorological conditions on the transportation of pollutants (Tayanc and Bercin, 2006). It is used for long-range transport modelling. It predicts both primary and secondary concentrations (Levy *et al,* 2002). It uses the scavenging and resistance-based approach to simulate the dry and wet deposition of pollutants. (MacIntosh *et al,* 2010).
ADMS	The Atmospheric Dispersion Modelling System is a steady-state Gaussian-like dispersion model designed to simulate short duration puff releases and continuous plumes (Carruthers *et al,* 1995). It is used to model buoyant and neutrally buoyant gases and particulates dispersed into the atmosphere (Carutthers *et al,* 1994). It simulates the spread of the plume by analytically formulating the distribution of concentrations (Riddle *et al,* 2004). It has the ability to quantify concentrations of pollutants from point, line, volume and area sources.
ISCT3	The Industrial Source Complex Short Term Model is a straight- line trajectory model. It assesses pollutant concentrations from industries (Wang *et al,* 2006). It is used for point, volume, area and open pit sources. The model is known to follow a normal distribution (Singh *et al,* 2006). It is used to model both rural and urban environments.
AERMOD	AERMOD modelling is a steady-state plume-dispersion model (Touma *et al,* 2007). It simulates essential atmospheric process and provides refined concentration estimates over a wide range of meteorological and modelling cases. It was developed as an improvement of the ISCT3 and its superiority is shown by a more refined treatment of the vertical structure of the Planetary Boundary Layer than the ISCT3 (Perry *et al,* 2005).

The model uses a fixed frame of reference that accounts for moving air parcels that flow through the geographical area of interest. This is done according to calculated wind fields. (Lin *et al*, 2011) They are used for both flat and complex terrains (Holmes and Morawska, 2006).

Lagrangian models do not use the steady-state assumption like the Gaussian models. They make use of the probability distribution of wind speed and direction. This is advantageous because they can support constant, time-varying and intermittent sources. They allow for four dimensions of wind shields. The wind-speed and direction vary in the vertical and horizontal extent over the modelling domain through time.

Lagrangian models are found in two paradigms i.e. puff and particle. In the particle paradigm the particles are emitted separately from the emission source. They are then treated individually as they move along the modelling-domain based on wind speed and wind direction. When it comes to puff models, a single puff emitted from the source contains many particles. Each puff has a specific initial length, width and height. The particles in each puff move separately on the basis of wind speed and direction, yet they maintain their own identity within the same puff. As the puffs move along the modelling domain they change shape and as they come in contact with the terrain e.g. buildings and mountains they may disintegrate into multiple puffs: some puffs may join to become a single puff.

Model inter comparison study for Matimba power station 2009

The study was undertaken in order to compare six models that differ in complexity. The models were run for six months (August 1991 to January 1992). The Matimba power station was the centre of domain. The modelled results were then compared with the monitoring results from the five monitoring stations sited at a distance ranging from 500 m to 29 km downwind of the power station (Figure 1.6). The monitoring campaign was conducted to monitor sulphur dioxide.

The models that were used were SCREEN3, ISC3, AERMOD, ADMS, CALPUFF and HAWK. AERMOD was not used as early-morning upper-air sounding data was not recorded in South Africa at the time of the running of the project (Rautenbach *et al*, 2009). The models were assessed according to their ability to predict the six months average, maximum one-hour and 24-hour averages and number of exceedences of the one-hour and 24-hour South African sulphur dioxide Standards that were acceptable at the time (Table 1.4).

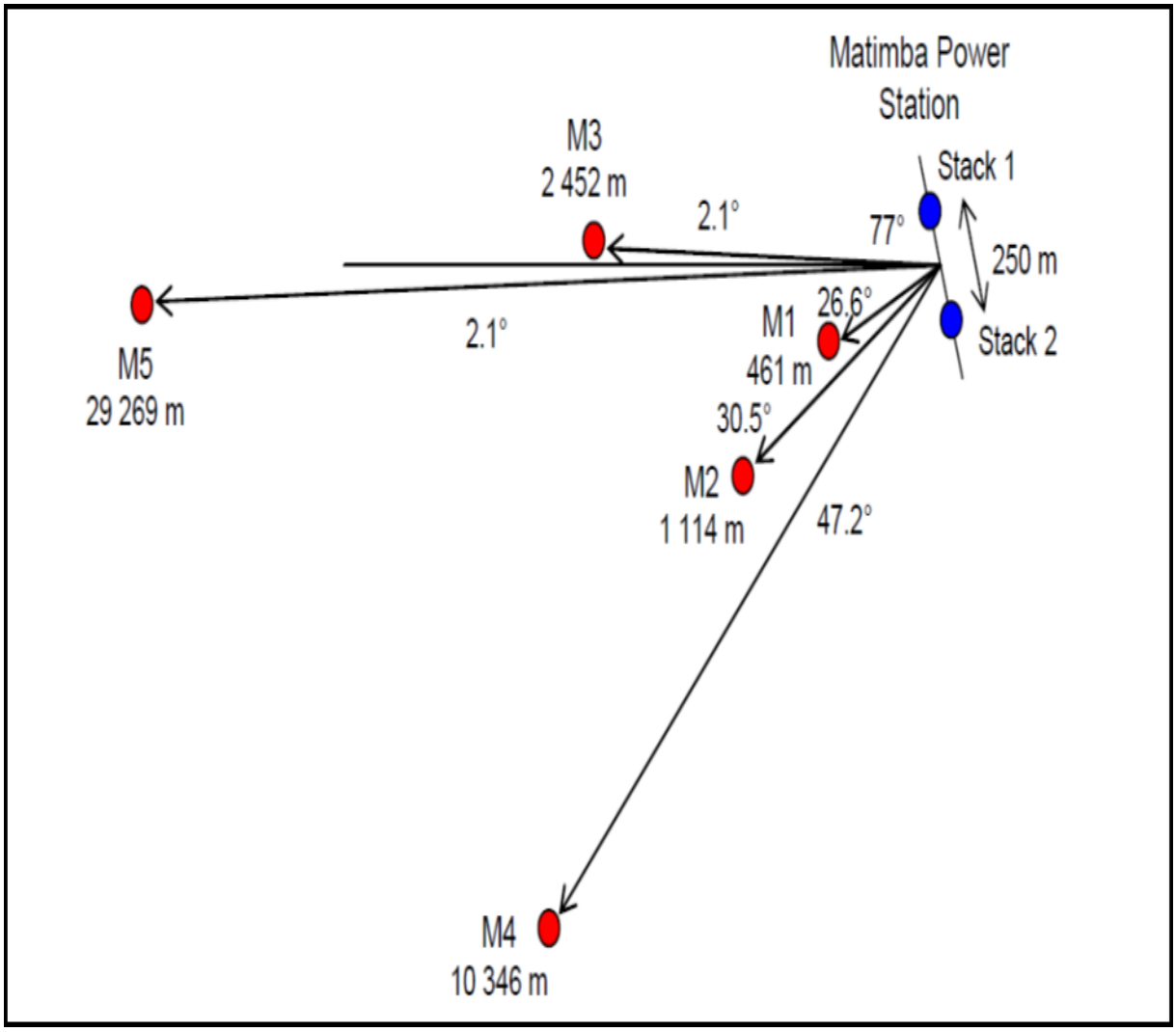

Figure 1. 6 Monitoring campaign layout (Rautenbach *et al*, 2009)

CALPUFF proved to be the most reliable pollution-dispersal model to be used at Matimba power station (Rautenbach *et al*, 2009). SCREEN3 was the least reliable method due to its conservative nature, ADMS and ISC3 followed CALPUFF respectively. CALPUFF proved to be the best model as it showed the influence of topography and offered the most accurate predictions of the spatial pattern of concentrations (Rautenbach *et al*, 2009).

CALPUFF seemed to predict more realistic concentrations than ADMS. Overall the models under- predicted the 6 months average and the 24-hour average SO_2 concentrations in distances below 2.5 km from the power station.

Table 1. 2 Comparison of Modelled and Measured SO_2 concentrations from the five monitoring stations (Rautenbach *et al*, 2009).

	Average ($\mu g.m^{-3}$)	1-hour maxi($\mu g.m^{-3}$)	Number of 1-hour exceedences	24-hour maximum ($\mu g.m^{-3}$)	Number of 24-hour exceedences	Avg/actual	1 hour max/ actual	24-hour max/ actual
Monitoring site 1								
measurements	9.60	361.90	1	65.61	0			
SCREEN3		1.4 E-6						
ISC3	0	0		0		0	0	0
ADMS	0.14	44.85	2.15	2.36	0	0.01	0.2	0.06
CALPUFF	0.55	249.29	0	14.07	0	0.06	0.69	0.21
Monitoring site 2								
measurements	13.45	509.52	1	63.15	0			
SCREEN3		3007					5.9	
ISC3	0.02	6.76		5.10		0	0.01	0.08
ADMS	2.01	687.21	565.9	20.84	0	0.15	1.35	0.33
CALPUFF	0.66	314.17	0	16.87	0	0.05	0.27	0.27
Monitoring site 3								
measurements	17.28	733.33	7	160.31	3			
SCREEN3		2160					2.95	
ISC3	0.34	803.29		47.03		0.02	1.10	0.29
ADMS	1.52	405.89	4	36.14	0	0.09	0.55	0.26
CALPUFF	0.78	182.88	0	19.30	0	0.05	0.25	0.12
Monitoring site 4								
measurements	12.21	442.86	1	78.83	0			
SCREEN3		938.3					2.12	
ISC3	16.47	986.10		814.85		1.35	2.23	10.34
ADMS	47.54	887.84	565.93	196.65	20.8	3.89	2.00	2.49
CALPUFF	19.91	943.57	39	136.06	0	1.63	2.13	1.72
Monitoring site 5								
measurements	12.33	602.38	2	102.20	0			
SCREEN3		538					0.89	
ISC3	2.13	437.31		437.26		0.17	0.73	4.28
ADMS	3.68	398.40	4.30	75.86	0	0.30	0.66	0.74
CALPUFF	2.23	173.71	0	30.58	0	0.18	0.29	0.30

Emission Factors

Emission factors are used as the most economically feasible tool to develop emission inventories (Environment Australia, 1999). They form an essential tool for air quality management and help with the identification of major atmospheric pollution sources, the invention of control strategies and other related activities. Environmental consultants and the industrial sector use emission factors as a tool (Environment Australia, 2001). It should be noted that emission factors cannot be used as an emission limit or standard for any pollutant. They are just an average value of category source within an area. Emission factors do not represent the average value of a specific pollutant source.

An emission factor is a value that is used to predict air pollutant emissions to the atmosphere. It attempts to relate the amount of pollutants released to activities associated with such emissions. Emission factors are depicted as the weight of pollutant divided by the unit's weight, volume, distance, or the timeframe of the activity emitting the pollutant (USEPA, 1995; Environment Australia, 1999; 2001).

Accurate emission factors help with the development of an emission inventory of an area. Both emission factors and emission inventories are important tools in air quality management (Walton and Ngkucana, 2009). Emission inventories help in:

- Formulating policies to manage air quality.
- Urban and regional planning.
- Designing regional monitoring networks.
- Predicting environmental impact.
- Providing spatial-resolved source data on pollutants for modelling activities.

A historical perspective on studies that have been done on air quality in Lephalale

Researchers have not conducted many air quality studies in the Lephalale area, with the exception of Eskom. Eskom has been at the forefront of research in Lephalale, conducting air quality studies for the past 30 years. Some of the most important studies will be discussed in this section to provide an outline of the air quality within the Lephalale area. These studies include the following monitoring campaigns:

- The continuous monitoring of air quality at the Waterberg substation 5km south-south-east of the power station -prior to and during the commissioning phase of the power station - as well as current monitoring activities.

- The air quality monitoring campaign during the year 2000 and 2001.
- The summer monitoring campaign from December 2004 to January 2005.
- The winter monitoring campaign during June-July 2005.
- The model inter-comparison study for Matimba power station 2009.

Air quality monitoring before and after the commissioning of the Matimba power station

The results of the monitoring studies have been useful in determining the ambient of the Matimba power station since it was commissioned in 1987. Monitoring began in 1984 before the power station started to operate. The continuous monitoring then showed that the power station had increased the level of sulphur dioxide since it became operational (Figure 1.7).

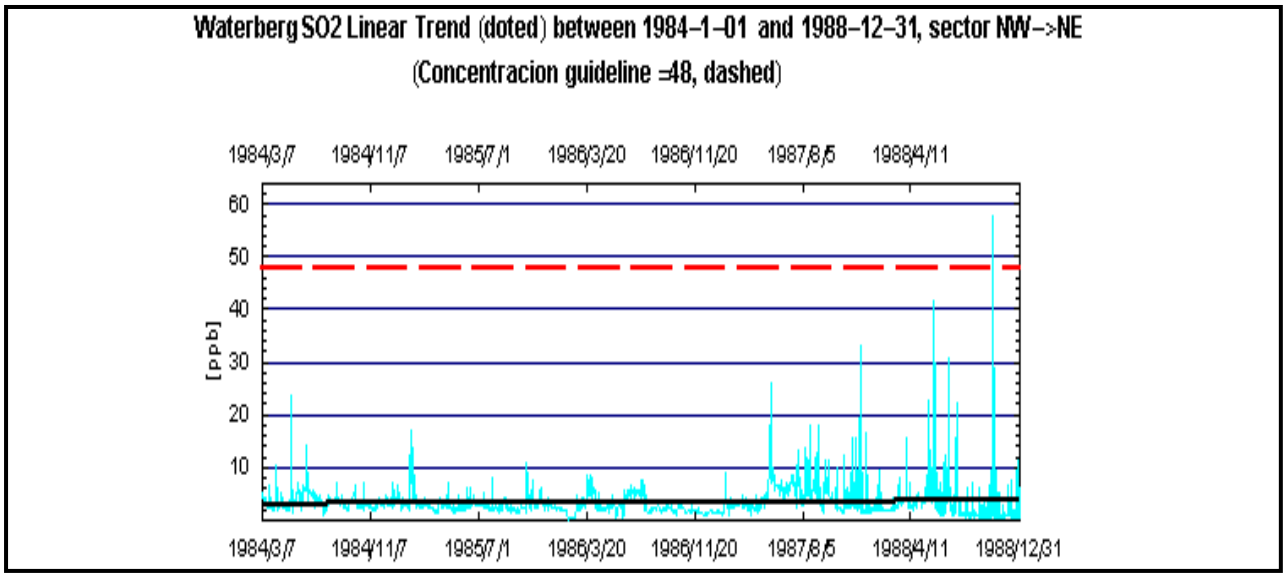

Figure 1. 7 Daily mean SO_2 concentrations that relate to the commissioning of the Matimba power station (Rorich, 2004)

Annual air quality monitoring campaign 2000 and 2001

During the year 2000 Eskom conducted an air quality monitoring campaign to determine the impact of Matimba power station and other sources that impact on air quality in the areas surrounding the power station. Previous modelling studies had indicated that higher ground level concentrations from the power station could be expected within 2.5 km from the power station stacks (Turner, 1993). Two monitoring stations were set up: at Grootegeluk Mine Guest house (16 km west-north-west of the power station) and Zaagput Farm (2.5 km from the power station). The monitoring station at the Grootegeluk Mine Guest House had to address the highest impact of the power station and the monitoring station at Zaagput farm

had to address the complaints lodged by the farm owner (Croucamp, 2001). The two monitoring stations recorded low values of pollutants. It was concluded that the low concentrations and low-level of exceedences above background concentrations were due to the fact that the monitoring stations were not situated within prevailing wind directions.
The Zaagput farm monitoring station was also too far from the major sources (Khumalo, 2002).

In 2001 it was decided to relocate the monitoring stations to more suitable locations in the area. The two monitoring stations were commissioned to be situated within the prevailing wind direction of west-north-west axis: downwind from the power station. They were then named Zwartwater and Hangklip. SO_2, Hydrogen Sulphide (H_2S) and Fine Particulate Matter (FPM) were recorded at Zwartwater, whereas Hangklip recorded only FPM.

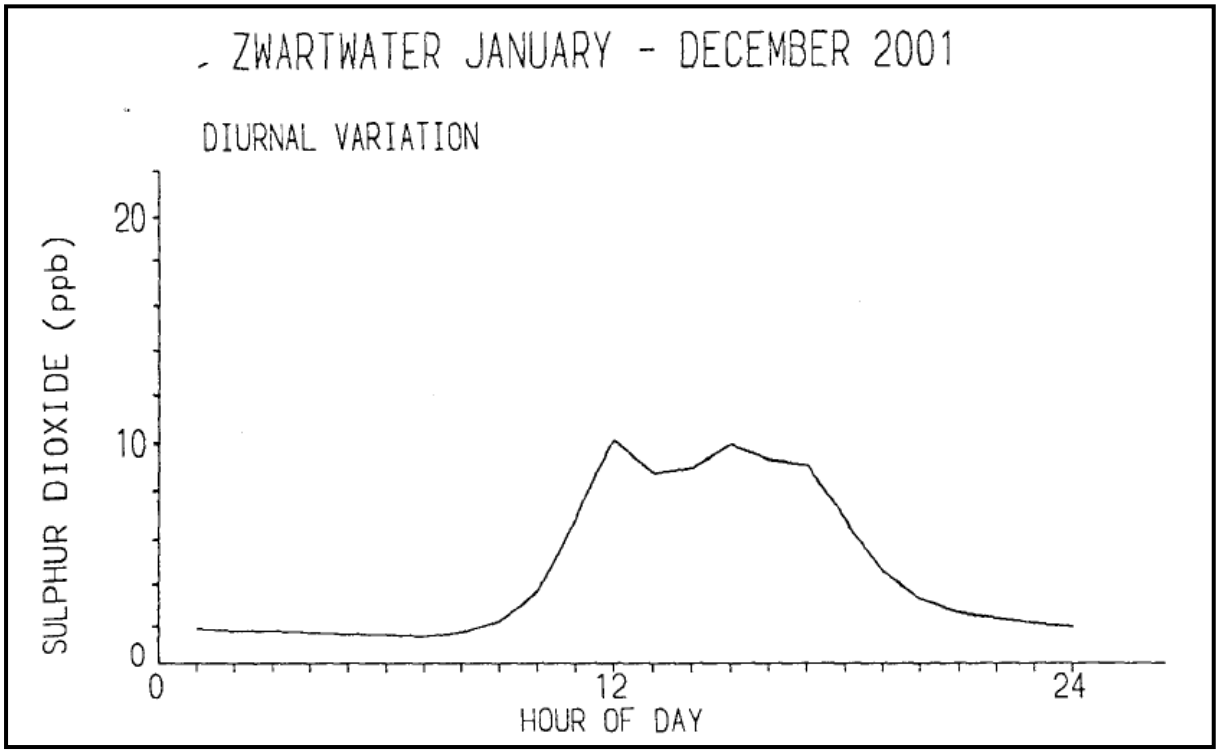

Figure 1. 8 SO_2 diurnal variations recorded at Zwartwater from January-December 2001 (Khumalo, 2002)

The SO_2 diurnal variation for emissions recorded at Zwartwater showed the typical signature for tall stacks (Figure 1.8). Higher values were recorded in the afternoon when pollutants mix due to turbulances. The levels of H_2S recorded were extremely low and they were assumed to be background concentration (Khumalo, 2002). The diurnal variation diagram of H_2S

indicated that the concentrations show a peak during the afternoon and decrease to background concentration during the evening (Figure 1.9). The power station was considered a minor source of H_2S and the major sources were considered to be the Grootegeluk mine and smouldering activities. This view was supported by the fact that higher values were from the west-north-west to west-north sector.

The diurnal variation for fine particulate matter (FPM) (Figure 1.10) shows a peak during the morning and it drops to background levels at 19:00. The Diurnal variation diagram shows a signature of tall stacks but may also be influenced by dust blown from level sources. This may be ascribed to wind speed which increased significantly during the day. There were problems with the monitoring station so the results indicated contain discrepancies.

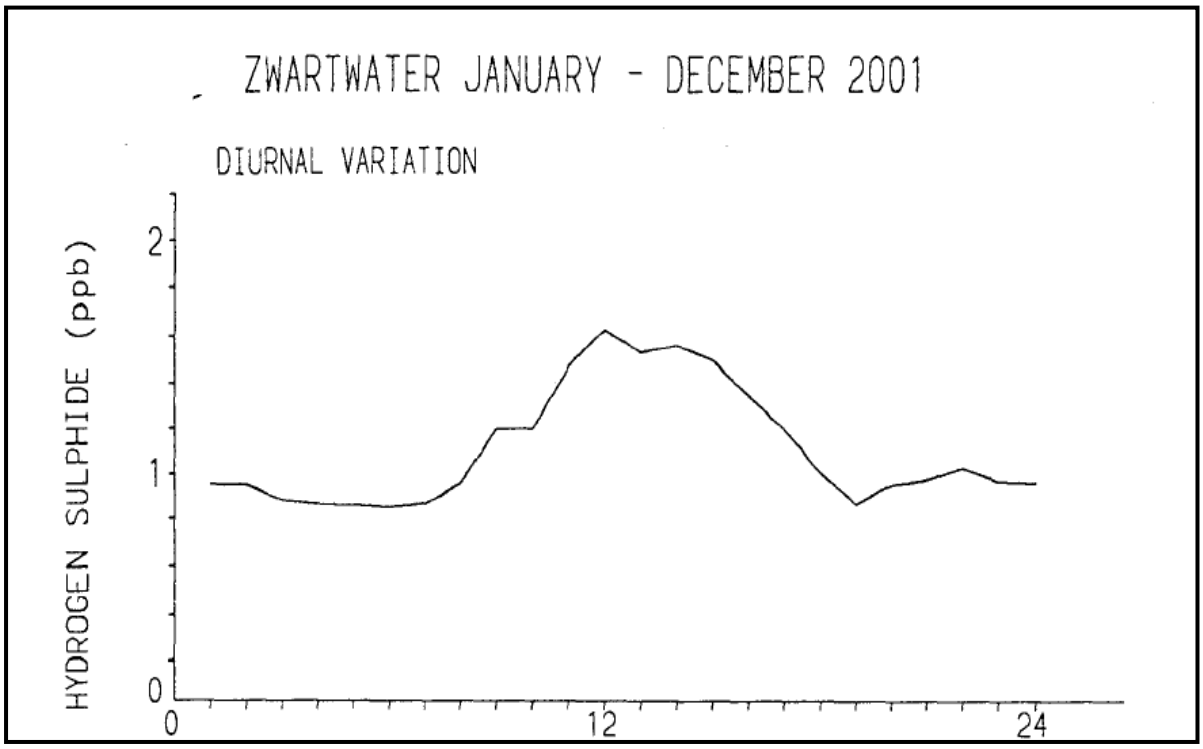

Figure 1. 9 H_2S diurnal variation recorded at Zwartwater from January-December 2001 (Khumalo, 2002)

The FPM diunal variation recorded at Hangklip monitoring station indicates a peak during the morning, and then drops sharply at 11:000. The peak is a signature of low-level sources (Figure 1.11). The peak is largely influenced by the dust blown from the ash disposal site and other low-level sources in the area. This is also supported by the wind speed diurnal variations.

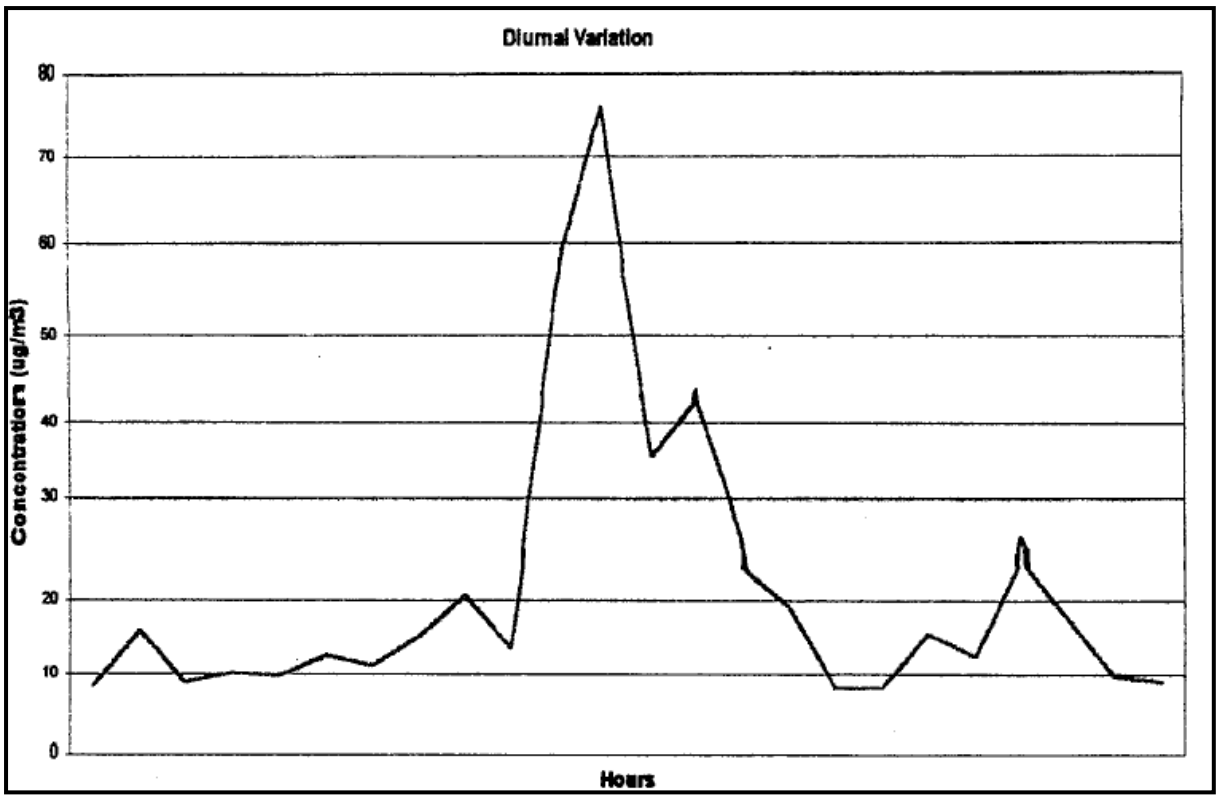

Figure 1. 10 FPM diurnal variation recorded at Zwartwater monitoring station from January-December 2001 (Khumalo, 2002)

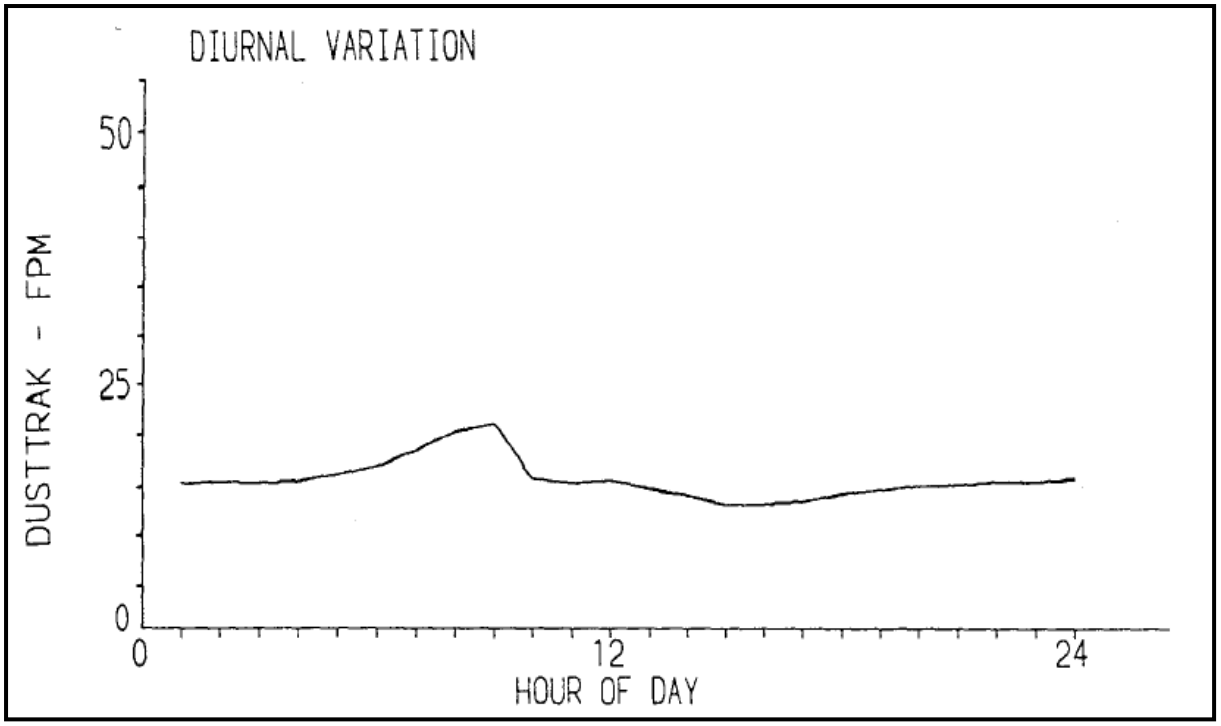

Figure 1. 11 FPM diurnal variations for Hangklip monitoring station recorded June 2001-January 2002 (Khumalo, 2002)

Summer monitoring campaign December 2004- January 2005

Real-time analysers were used to monitor the ambient air quality impact of both Matimba and Grootegeluk mine in the area. They were placed 7km (Buffelsjagt farm) downwind of the two sources in a west-south-west direction.

Even though many peaks were recorded throughout the monitoring period, they never exceeded the hourly standard (191 ppb). The diurnal variation showed a typical tall stack signature (Figure 1.12). The highest concentrations were recorded at 13:00 and most concentrations were around 25 ppb. The pollution rose depicted that most SO_2 came from the east-north-east sector that aligns with the power station.

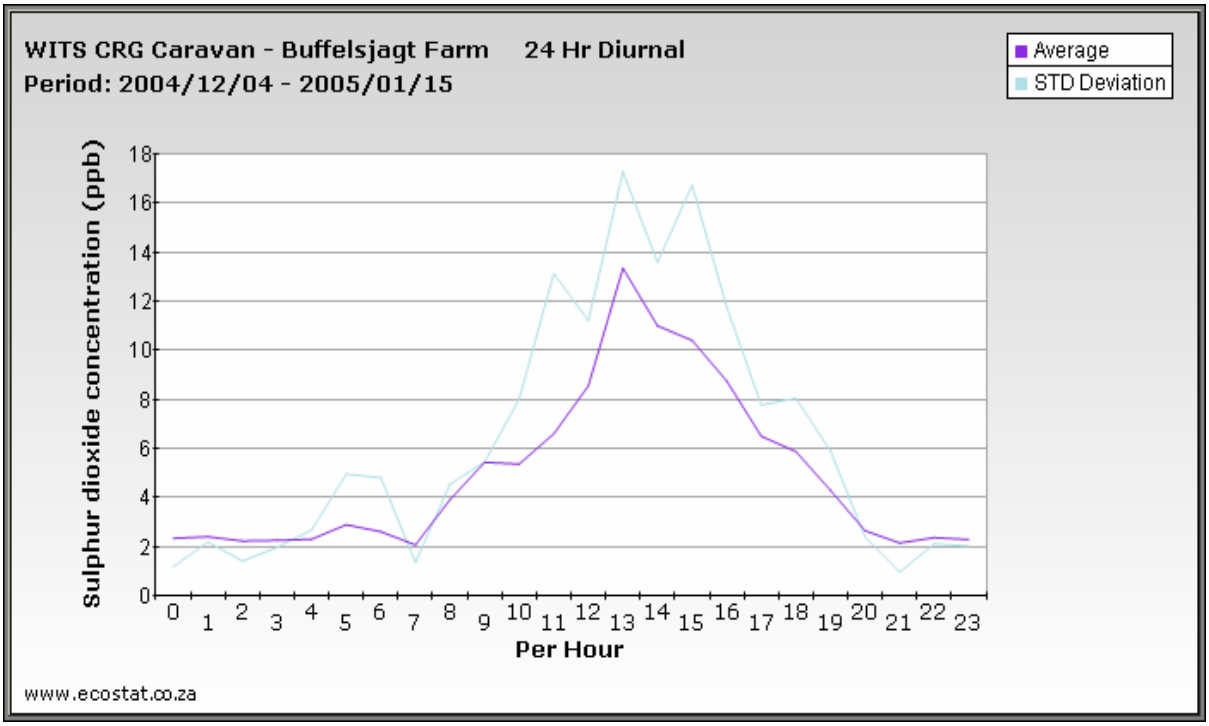

Figure 1. 12 Diurnal pattern of impact of SO_2 at Buffelsjagt Farm during the summer monitoring campaign (Keir *et al*, 2007)

Hydrogen sulphide (H_2S) values for the study were derived from subtracting SO_2 values from the total sulphur recorded. The H_2S values were fairly low and they were generally low throughout the monitoring campaign. The peaks seldom exceeded 5ppb.

During the monitoring period nitric oxide (NO) concentrations were low and they never exceeded 20ppb (Figure 1.13). The power station was ruled out as the largest contributor of NO during the day. A distinct source of NO from the south-east was identified during night time. The (Nitrogen dioxide) NO_2 recorded during the monitoring period was fairly low and

never exceeded 27 ppb. Ozone (O_3) was also investigated in the study. The highest concentration recorded was 65 ppb. The pollution rose did not indicate the particular direction of the source of the O_3. Its diurnal variation did not follow the same photolysis pattern as NO and NO_2. The amount of nitrogen dioxide (NO_2) recorded did not attribute to the rest of O_3 formed. It was recommended that further studies should be done to determine the main source of ozone.

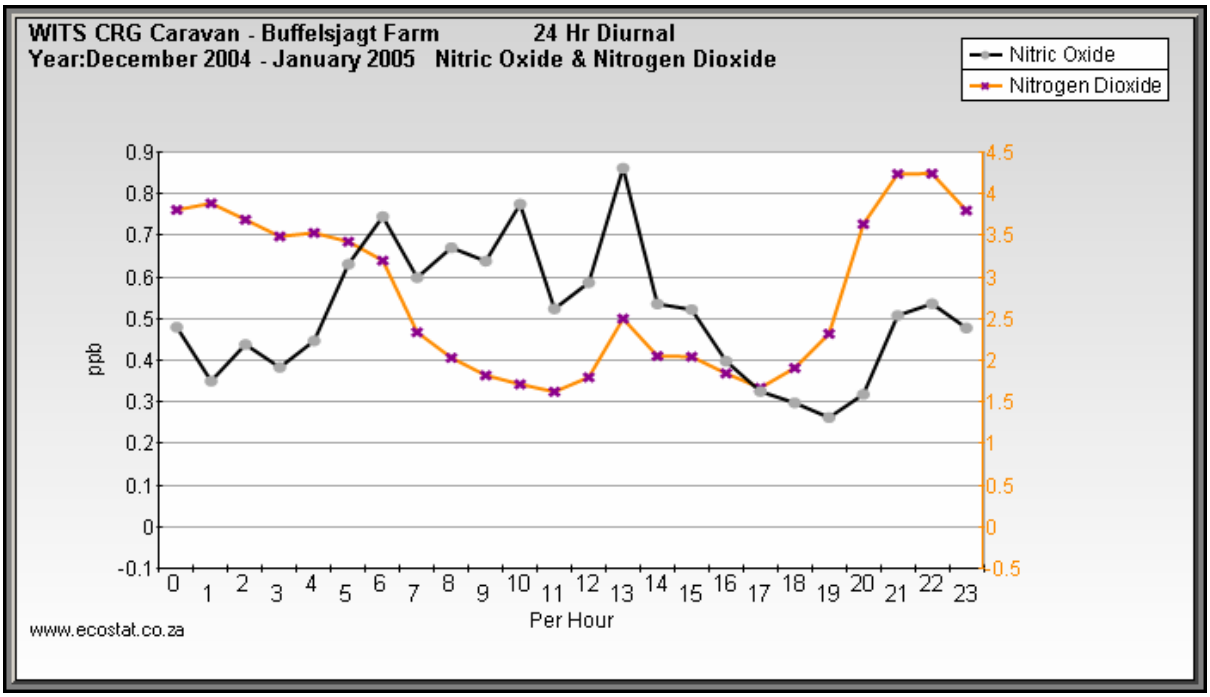

Figure 1. 13 Diurnal impact of NO and NO_2 at Buffelsjagt site during the summer monitoring campaign (Keir *et al*, 2007)

Carbon Monoxide (CO), PM_7 and PM_{10} were also recorded. PM_{10} showed more elevated concentrations than PM_7. All these pollutants did not show any specific diurnal pattern. The pollution roses of particulate matter and CO didn't show the specific direction of the source of the pollutants. This suggested that they possibly came from diversified sources: the power station, the colliery, various agricultural activities and other sources such as motor vehicles.

Winter monitoring campaign June-July 2005

The winter monitoring campaign was undertaken in the vicinity of the opencast pit of the Grootegeluk mine to determine its impact on the air quality. A slight change of the direction of the wind to the northerly sector was observed when comparisons were made to the summer campaign.

SO_2 concentrations measured at Grootegeluk were high and the maximum value recorded was 130 ppb. Its diurnal variation showed the same signature as the one from Buffelsjagt (Figure 1.14). Its pollution rose showed that most pollutants came from the east. The power station is located slightly north of east. This confirmed that the power station was the major source of SO_2. H_2S is known to be an excellent tracer of spontaneous combustion. It was therefore expected that H_2S would be from the colliery. The highest value of H_2S recorded was 65 ppb. The signature of H_2S was that of bimodal diurnal variation at the colliery (Figure 1.15). This indicated that H_2S came from a low-level source that emits H_2S to the surface inversion.

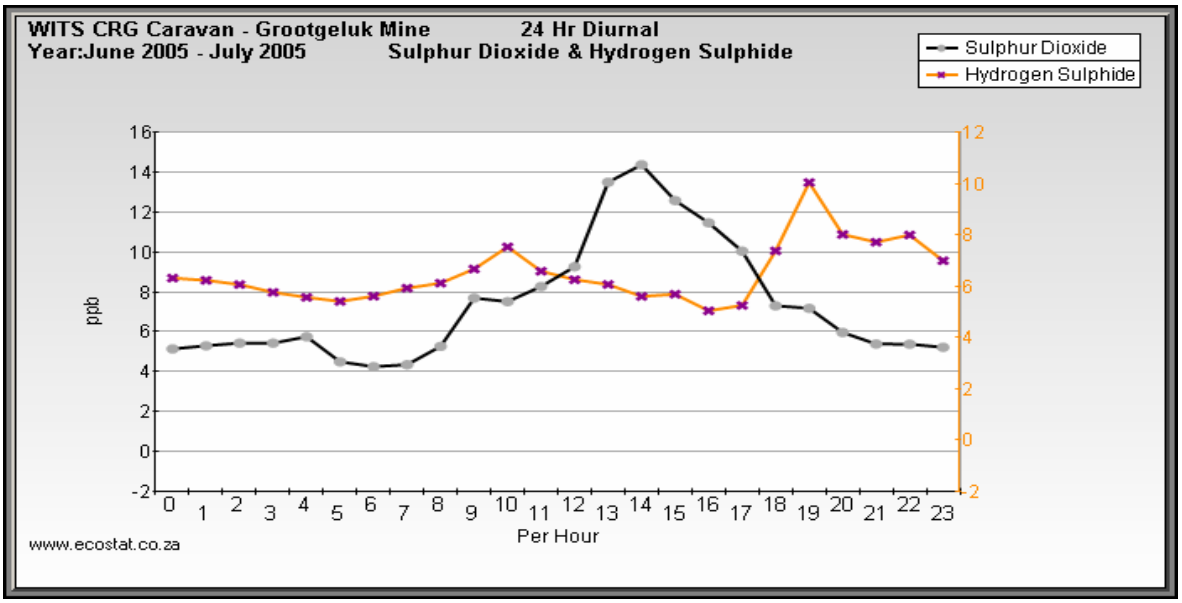

Figure 1. 14 Diurnal patterns of SO_2 and H_2S detected at Grootegeluk colliery site during the winter monitoring campaign (Keir *et al*, 2007).

NO concentrations recorded at the mine during the winter monitoring campaign were higher by a factor of 10 than the ones recorded during the summer campaign. Its signature was that of bimodal diurnal variation (Figure 1.14) The NO_2 recorded at the mine was significantly higher than those recorded during the summer campaign. The diurnal variation of NO, NO_2 and H_2S were similar. This confirmed that the mine was the major source of those pollutants. Unlike the results at Buffelsjagt, this study concluded that photolysis did not play a major role in the production of NO_2.

NO_x concentration played a role in the formation of O_3 at the mining site. The winter concentrations at the mining site were lower than those recorded at the Buffelsjagt in the summer. The highest concentration recorded was just 40 ppb.

The spontaneous combustion from the mine was identified as the major source of CO at the site. The diurnal variation indicated that concentration reached 1 ppb most hours of the day. The diurnal variation pattern was different from that shown by H_2S, NO and NO_2. The concentration of CO rises from the morning time and then drops after 20:00. The pattern indicated that there are also other sources of CO in the area.

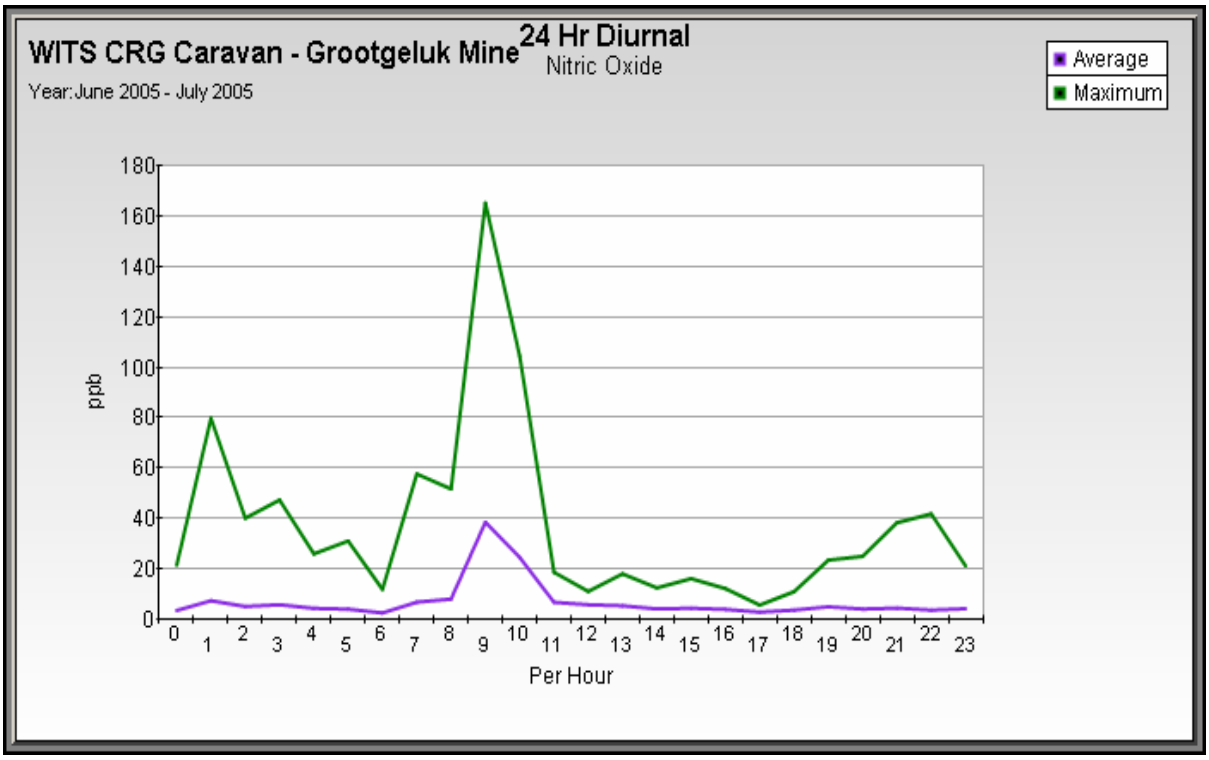

Figure 1. 15 Diurnal pattern of NO at Grootegeluk site during the winter monitoring campaign (Keir *et al*, 2007)

It was expected that the concentration of PM_{10} at the mine would be high. The highest recorded value was 1900 µg/m^3. From the diurnal variation -which was similar to that of NO -it was concluded that most PM_{10} came from vehicles and machineries operating at the mine. VOC's were also recorded at the mine and it was concluded that the mine was the major source of these pollutants.

Air quality legislation in South Africa

The National Environmental Management Act (NEMA) (Act 107, 1998) is the legislation by which South Africa's environment is managed. NEMA sets out a series of environmental principles to guide the application and interpretation of all legislation that impact on the environment. The National Environmental Management: Protected Areas Act, 2004 (Act 57 of 2004), the National Environmental Management: Biodiversity Act, 2004 (Act 10 of 2004)

and the National Environmental Management: Air Quality Act, 2004 (Act 39 of 2004) (AQA) are the specific environmental statutes that have been promulgated under the NEMA framework since 1998.

Prior to the promulgation of AQA in 2004, the air quality in South Africa was controlled by the Atmospheric Pollution Prevention Act (Act 45 of 1965) (APPA) (Department of Environmental affairs, 2005). APPA used the source-based approach and put guidelines in place for stack emission for various common pollutants (UNEP/WHO, 1996) (Table 1.3).

Table 1. 3 Differences between approaches used by APPA (1965) and NEM: air quality act (2004)

APPA 1965	**NEM:AQA 2004**
National Government had control and was responsible for enforcement of the act.	Local Government responsible for enforcement and control, national government responsible for policy development.
Source-based approach.	Receptor-based approach.
Emission reduction measures were prescribed.	Emission reduction measures are subjected to licensing. The license holder can develop emission reduction measures and submit them for acceptance by the competent authority.
National government was solely responsible for evaluation, monitoring and accountability measures.	AQA, other policy and guidance materials have been developed to assist the license holder with monitoring and reporting.

The APPA was ineffective because it focused mainly on industrial emission control and neglected emission controls of noise, dust and vehicles (Naiker *et al*, 2012). It did not set standards that had to be adhered to and it made no provision for compliance and enforcement. The use of guideline values that could not be legally enforced was perceived as one of its major shortcomings (Scott *et al*, 2005). Further criticism of the APPA was that it was essentially not proactive in its measures to improve the air quality (Barnard, 1999). Critics alleged that the APPA was biased because negotiations on best practice took place between the government and the industrial representatives.

Table 1. 4 Summarised South African National Ambient Air quality Standards (DEAT, 2004)

Pollutant	**Averaging period**	**Immediate**	**2015**	**Frequency of Exceedences**
Sulphur dioxide (SO_2)	10 minutes	500 µg/m^3 (191 ppb)	_	526
	1 hour	350 µg/m^3 (134 ppb)	_	88
	24 hour	125 µg/m^3 (48 ppb)	_	4
	1 year	50 µg/m^3 (19 ppb)	_	0
Nitrogen dioxide (NO_2)	1 hour	200 µg/m^3 (106 ppb)	_	88
	1 year	40 µg/m^3 (21 ppb)	_	0
Carbon Monoxide (CO)	1 hour	30 µg/m^3 (26 ppb)	_	88
	8 hour	10 µg/m^3 (8.6 ppb)	_	11
Particulate Matter (PM_{10})	24 hour	120 µg/m^3	_	4
	24 hour		75 µg/m^3	4
	1 year	50 µg/m^3	_	0
	1 year		40 µg/m^3	0
Ozone (O_3)	8 hour	120 µg/m^3 (61 ppb)	_	11
Lead (Pb)	1 year	0.5 µg/m^3	_	0
Benzene (C_6H_6)	1 year	10 µg/m^3 (3.2 ppb)	_	0
	1 year	_	05 µg/m^3 (1.6 ppb)	0

When the AQA was promulgated in 2004 it made provision for:

- A national air quality framework.
- The establishment of national and local ambient air quality and emissions standards.
- The declaration and management of priority areas where air quality is of particular concern.

- A list of activities that would require an atmospheric emissions licence.
- A list of controlled emitters and controlled fuels.
- A range of new criminal offences.

The AQA mandates that norms, standards, mechanisms, systems and procedures be issued to improve air quality (Liebenberg-Enslin *et al*., 2007). It establishes the national framework within which these standards can be set. It gives the Minister of Environmental Affairs and Tourism and the members of the Executive Council of a province (MEC) the authority to issue standards, enforce regulations and other measures. It also gives them the authority to implement penalties for non-compliance and to establish funding arrangements (Department of Environmental affairs and Tourism, 2008; Scott, 2005).

The AQA has the constitution as its foundation (Department of Environmental Affairs and Tourism, 2005). It is responsible for the establishment of national norms, standards (Table 1.4) and control of emissions. The ambient air quality standards ensure the protection of the environment and human health as it enforces regulations and continuously monitors pollutants.

Sources of air pollution in Lephalale

Power station

The Matimba power station is located within the Lephalale area (coordinates, 23° 40' 06 "S and 27°36' 38" E) (Figure 1.16). It is the biggest direct dry-cooled power station in the world. It was designed as a dry-cooled power station because of a shortage of water within the Lephalale area. The power station is located approximately 14 km west of the commercial centre of Lephalale and 8 km west-north-west of Onverwacht, a residential suburb. The power station comprises of 6 x 660 MW(e) pulverised fuel boilers which were commissioned between 1987 and 1991 and is operated primarily as a base load. Electrostatic Precipitator and Flue Gas Condition Plants (SO_3) were installed in Matimba power station to reduce particulate emissions. At the moment there is no SO_2 emission control equipment installed at Matimba. Material-handling operations -such as the transfer of coal within the power station - are one of the sources of pollutants. Windblown dust from ash dump and stockpiles is another source. The possible pollutants from Matimba power station are sulphur dioxide, carbon monoxide, nitrogen oxides, particulate matter and trace amounts of mercury.

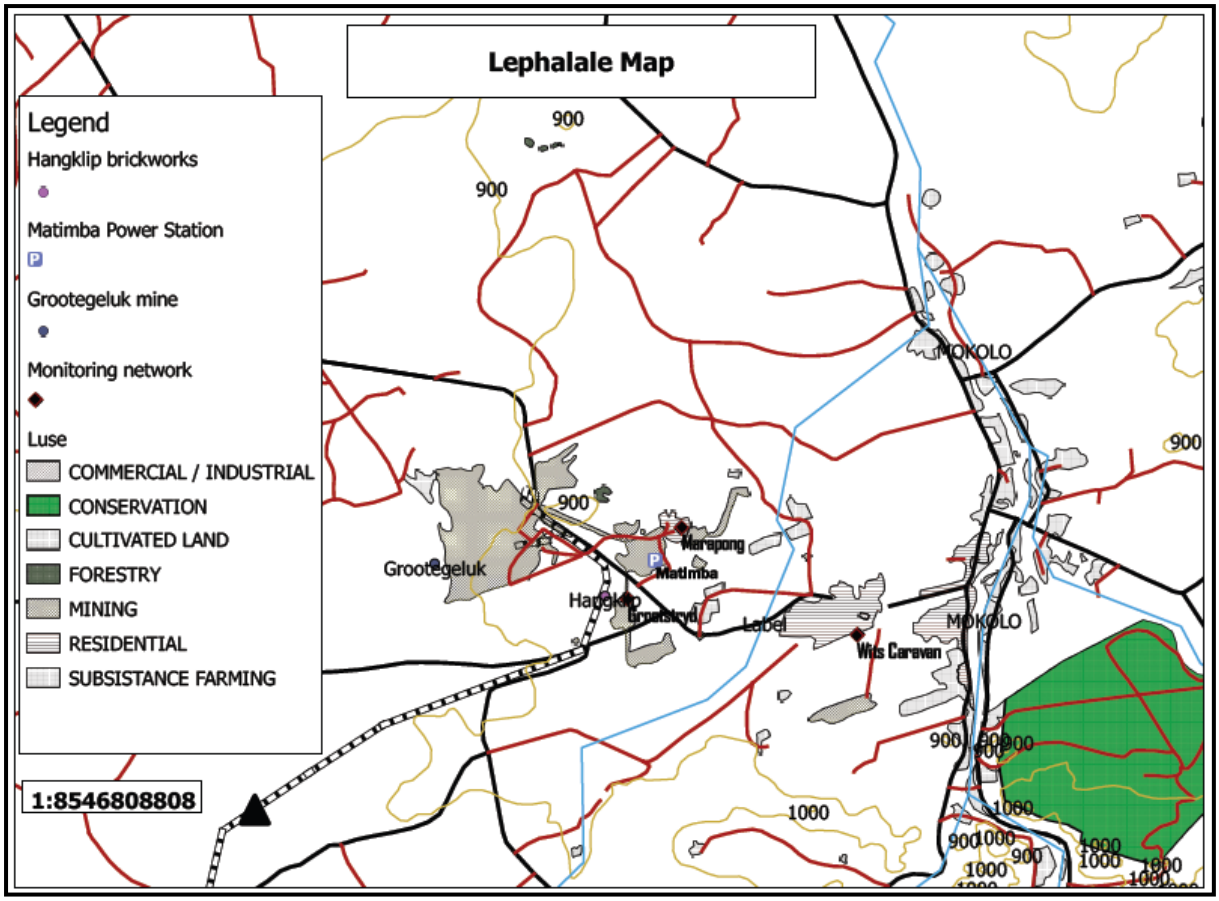

Figure 1. 16 Location of Matimba power station and monitoring network in proximity to Grootegeluk mine

Grootegeluk Mine

Grootegeluk Coal mine is located 25km from the Lephalale town (Figure 1.16). It is a conventional open-pit mine and has five processing facilities. The sixth one is under construction. The coal that is produced is transported to Matimba power station via a 7 km conveyor belt.

Possible emissions from the mine that could impact on the air quality of the area are from coal exploitation, transportation and crushing. Small quantities of sulphur dioxide, nitrogen oxides, carbon monoxide and hydrogen sulphide are formed through the process of spontaneous combustion.

Domestic (Household) Burning

A wide variety of sources of energy is used in townships. Coal and bio-fuel are used for cooking and heating especially during winter months (Mdluli and Vogel, 2010; Tummon *et al*, 2010). There are numerous other small-scale, loosely regulated combustion sources such

as the domestic use of biomass fuel, the burning of garbage and crop residues that is common practice in developing countries (Christian *et al*, 2010). Some of the pollutants released into the atmosphere during domestic burning are sulphur dioxide, carbon monoxide, carbon dioxide, nitrogen oxides, methane and Volatile Organic Compounds. The surface emissions due to the domestic burning of coal and biomass burning – especially in the winter when they are used to warm up homes -are the most significant contributors to surface emissions in South Africa (Piketh *et al*, 1999).

Even though most of the houses in the Lephalale region have access to electricity, the majority of the households use wood, paraffin and coal for cooking, lighting and heating. A community survey that was conducted in 2007 indicated a decline in fuel-usage compared to 2001. This can be attributed to an increase in electrified houses in the area. Most households rely predominately on wood as their other source of energy. Table 1.5 to 1.7 indicate the number of households and the different fuel types that are used as sources for heating, cooking and lighting.

Table 1. 5 The number of households and fuel type used for cooking in Lephalale (Statistics South Africa, 2001)

Fuel	**Ward 1**	**Ward 2**	**Ward 3**	**Ward 4**	**Ward 5**	**Total number of households**
Electricity	1525	2284	830	1034	1362	1034
Gas	22	33	5	64	80	64
Paraffin	547	41	45	161	267	161
Wood	91	530	22	2543	2906	2543
Coal	2	1	0	5	13	5
Animal dung	1	4	5	3	13	3
Solar	8	13	0	7	16	7

Table 1. 6 The number of households and fuel type used for heating in Lephalale (Statistics South Africa, 2001)

Fuel	**Ward 1**	**Ward 2**	**Ward 3**	**Ward 4**	**Total number of households**
Electricity	2301	838	1077	1468	7213
Gas	22	6	46	69	148
Paraffin	26	33	125	214	809
Wood	541	15	2503	2807	6085
Coal	1	1	10	14	28
Animal dung	2	111	0	3	16
Solar	5		2	9	28

Table 1. 7 The number of households and fuel type used for lighting in Lephalale (Statistics South Africa, 2001)

Fuel	**Ward 1**	**Ward 2**	**Ward 3**	**Ward 4**	**Total number of households**
Electricity	1635	2438	1667	2584	9176
Gas	3	12	19	7	56
Paraffin	36	16	115	161	355
Wood	528	422	1944	1894	3804
Coal	_	_	_	_	_
Animal dung	_	_	_	_	_
Solar	1	13	8	0	35

Motor Vehicles

An increase in population is usually evident in a town when new industries are formed. This leads to an increase in traffic. The construction of the Medupi power station and other mineral exploitation activities has led to an increase in traffic in Lephalale. Authorities have consequently constructed a new road passing the Wits monitoring caravan in New Road. Transportation creates major pollutants such as SO_2, NO_x, CO and particulate matter from tyre and brake wear (Rhys-Tyler *et al*, 2011). NO_x is formed mainly in the engine from the reaction of nitrogen and oxygen under high temperatures. SO_2 emissions from motor vehicles depend mainly on the sulphur content in the fuel. Various studies have indicated traffic as a major factor in the deterioration of ambient air quality.

The increase in traffic in Lephalale, the presence of the power stations and other industrial activities will have a cumulative detrimental effect on air quality. The effects of specific factors in relation to traffic as a factor in air quality are also to be taken into consideration. These factors include: vehicle class, model, fuel delivery system, vehicle speed and maintenance history. Fuel related factors such as fuel type, oxygen, sulphur, Benzene and lead content also have an influence on vehicle emission rates (Samaras and Sorensen, 1999).

Hangklip brickworks

The Hangklip brickworks produce approximately 24 million bricks annually (Walton and Ngcukana, 2009). The method used by the brickworks is regarded as the oldest method of brick-making: clamp kilns. During the process of making bricks, clay minerals are separated and concentrated by screening, floating, wet and dry grinding and blending of raw materials. The bricks are then cut, shaped, dried and fired until the desired product is made.

Emissions from the manufacturing of bricks come primarily from the handling of raw materials, processing and plant maintenance. Sulphur dioxide, nitrogen dioxide and carbon dioxide are formed by the combustion processes. Small amounts of volatile organic compounds and hydrochloric acid are also produced.

> The outline of the sources of pollutants in Lephalale area has been discussed. Dispersion of pollutants in the atmosphere, dispersion of pollutants from tall stacks and dispersal of pollutants from low-level sources has been outlined. The previous studies done in Lephalale, before and after the Matimba power station was constructed, were discussed. Pollution dispersion modelling was also

outlined. Data and methods used in this dissertation will be outlined in chapter two.

Chapter 2: Data and Methods

This chapter outlines all the air quality monitoring data used in this research. It also gives an overview of the AERMOD model. All the data used as input to the model are highlighted.

Ambient air quality data

The ambient air quality data was obtained from Eskom's Climate Change, Air Quality and Ecosystem Management department's database. Two monitoring sites were chosen for the purpose of this study i.e. Grootstryd and Marapong monitoring stations. The available data from Grootstryd was for the period 2005-2006. Marapong Site was commissioned in 2007 and data was available for this project until 2010.

All the ambient air quality data used in this research was analysed using Microsoft Excel and EDWEIS. EDWEIS is an ambient air quality database and analysis tool that was developed by Eskom. The software allows the user to perform basic analysis, such as pollution roses, wind roses and diurnal variations for ambient air quality monitoring.

Data recovery

Figure 2.1 The ambient air quality monitoring station with a PC laptop logging data

All Eskom's ambient air quality monitoring stations (Figure 2.1) are set up and operated in accordance with the standards set by the United States Environmental Protection Agency (USEPA). Both Grootstryd and Marapong monitoring stations are visited on a monthly basis for routine servicing and analyser zero span checks. Data collection is done twice within one month. The data is transferred to a Personal Computer (Figure 2.1) laptop and taken to the Eskom Research and Innovation Centre for processing and analysis. All the monitoring stations are fitted with air-conditioning units to ensure that all the instruments operate within the specifications set by the manufacturers.

Quality Control

Eskom has a quality assurance programme in place to ensure that the data recovered from the air quality monitoring stations is of a high quality. All monitoring stations are serviced every fortnight as per ISO 9000 site service procedure 60P2084. Zero and span checks are carried out on each analyser and the discrepancies are logged and used during data verification at the Eskom Research and Innovation Centre.

Calibration is carried out in the Environmental laboratory that is accredited by the South African National Accreditation System (SANAS). On-site calibration is also done and is carried out in accordance with SANAS specifications. Both Grootstryd and Marapong monitoring stations have been monitored by the Desert Research Institute of Nevada and were found to be fully compliant with USEPA standards.

Site Reliability

The parameters measured at the two monitoring stations are indicated in the table below. It should be noted that Grootstryd only operated from 2005-August 2006 whereas Marapong operated from 2007 till present. This study will only use data from 2007-2010.

Only parameters relevant to this study will be indicated on the table. It is important to note that NO_x was only monitored at Marapong.

The overall percentage data recovery of Grootstryd was 87.72 % in 2005 and 85.13 % in 2006. In Marapong monitoring site the overall data recovery for the period 2007, 2008, 2009 and 2010 was 84.3 %, 85.10 %, 81.78 % and 91.57 % respectively (Table 2.1).

Table 2. 1 Percentage data recovered at both Grootstryd and Marapong Monitoring stations

Year	parameters	Percentage recovered
2005	Wind direction	89.11
	Wind speed	89.11
	Sulphur dioxide	84.93
2006	Wind direction	88.63
	Wind speed	88.63
	Sulphur dioxide	78.14
2007	Wind direction	97.00
	Wind speed	97.00
	Sulphur dioxide	89.00
	Nitric oxide	83.30
	Nitrogen dioxide	79.70
	Nitrogen oxides	79.70
2008	Wind direction	93.72
	Wind speed	98.52
	Sulphur dioxide	85.96
	Nitric oxide	77.48
	Nitrogen dioxide	77.45
	Nitrogen oxides	77.45
2009	Wind direction	87.39
	Wind speed	87.39
	Sulphur dioxide	79.10
	Nitric oxide	78.97
	Nitrogen dioxide	78.91
	Nitrogen oxides	78.91
2010	Wind direction	94.33
	Wind speed	94.33
	Sulphur dioxide	90.40
	Nitric oxide	90.12
	Nitrogen dioxide	90.11
	Nitrogen oxides	90.11

AERMOD Modelling

The AERMOD modelling system is a steady-state Plume dispersion model. It simulates the dispersion of pollutants at a distance of less than 50 km. The predictions are based on boundary layer turbulent structure and scaling concepts (Zou, 2010). The model assumes that concentrations at all distances during a modelled hour are controlled by a set of hourly meteorological inputs which are held constant (Touma *et al*, 2007). It was developed by the American Meteorological Society and the United States Environmental Protection Agency.

AERMOD simulates essential atmospheric processes and provides refined concentration estimates over a wide range of modelling and meteorological cases (Touma *et al*, 2007). It is built on an earlier pollution dispersion model named Industrial Source Complex Short-Term 3 (ISCST3). An improvement on the ISCST3 is shown by the ability of AERMOD to treat the vertical structure of the planetary boundary layer (PBL) dynamically rather than treating it simply as the ISCST3 does (Perry *et al*, 2005).

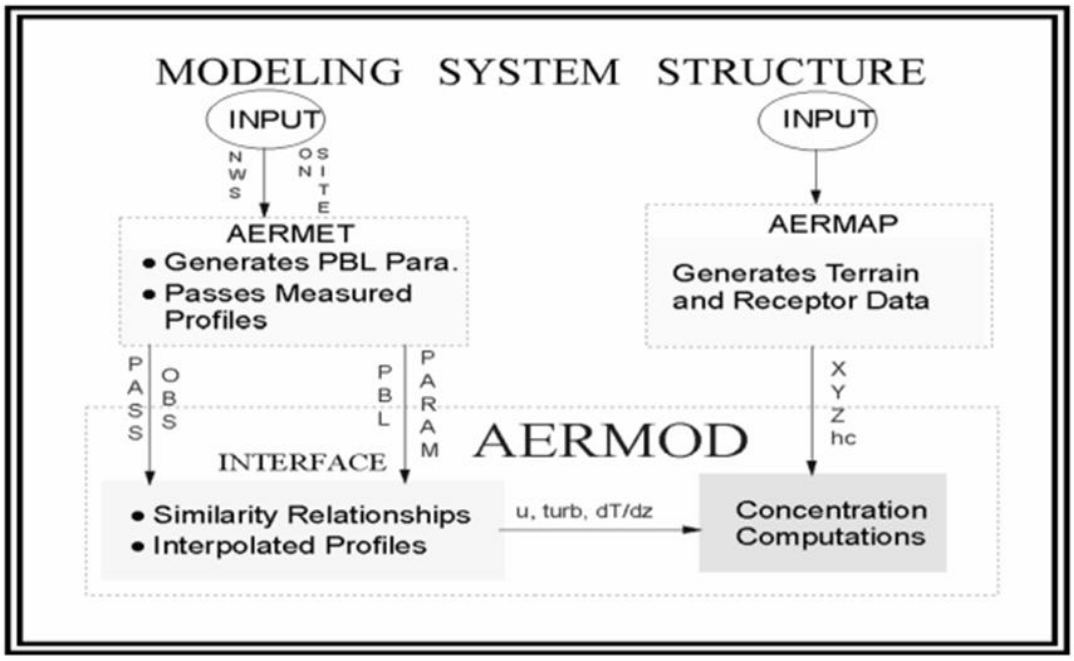

Figure 2.2 AERMOD modelling system structure. AERMET is used for Meteorological input whereas AERMAP is used to generate terrain data and receptor data (After Touma *et al*, 2007)

AERMOD Modelling system is constituted by two pre-processors (Figure 2.2): AERMAP (AERMOD terrain pre-processor) and AERMET (AERMOD meteorological pre-processor). AERMET provides AERMOD with meteorological data in order for it to characterize the

Planetary Boundary layer (PBL). With such meteorological data (e.g. cloud cover, wind speed, temperature and wind direction) the model computes Monin-Obukhov equation, surface mixing height, convective velocity scale and surface heat flux (Cimorelli *et al*, 2005).

The meteorological data is divided in two: upper air data and surface data. The data is analysed using the Julian calendar (Kumar *et al*, 2006). Obtaining upper air data over South Africa is often problematic as upper air data is not collocated with surface observation data. It might therefore not be representative of the investigation site (Isakov *et al*, 2007). The upper air data is obtained from the South African Weather Services. Problems arise when the weather stations are far away from the area where AERMOD is being run. In those instances they are no longer considered as being representative (Isakov *et al*, 2007). The use of prognostic models with AERMOD is very useful and it produces reliable results (Touma *et al*, 2007, Kesarka *et al*, 2007). When AERMET processes meteorological data, three stages are followed. From this process two files are generated to use within the AERMOD model:

- A Surface file of hourly boundary layer parameters estimates.
- Profiles of observations from multiple levels of wind direction, wind speed, temperature, and standard deviation of the fluctuating wind components (Saqer and Al-Hadaad, 2010)

AERMAP is used to calculate terrain and critical hill height values for each receptor for use in AERMOD (Touma *et al*, 2007). The terrain data is calculated based on the UTM coordinate system. In South Africa WGS 84 is used. It also generates reception grids into the dispersion model. It has been developed to process terrain data in conjunction with a layout of receptors and sources to be used in AERMOD files.

Model configuration and input data

This section describes the procedure that was used to determine the ambient air quality impact of the power stations in Lephalale area. The AERMOD pollution dispersion model was run for a 2500km^2 area. The procedure is explained below.

AERMOD initialization

The modelling period of January- December 2010 was used even though Eskom monitoring data for Marapong monitoring station was from 2008-2010. The model was used to simulate SO_2 and NO_x concentrations at 1 hour, daily and annual averages. The Model was configured

for urban dispersion co efficient and flat terrain. The emission source was considered to be Matimba power station.

Emission sources as model inputs

The emissions of sulphur dioxide and nitrogen dioxide were estimated based on the principle of conservation of mass. It was assumed that sulphur in the coal would react with oxygen during combustion and be emitted as sulphur dioxide. The stack parameters used by the model are indicated in Table 2.2. The formulas that were used to calculate the gaseous emissions from the power station are discussed below:

Table 2. 2 Emissions data used as input to run AERMOD model

MATIMBA POWER STATION	
Stack height	250 m
Stack temperature	132°C
Number of stacks	6
Stack diameter	8 m
Total stack area	1206.37 m^2
Effective stack diameter	12.82 m
Stack exit velocity	0.46 m/s

The monthly sulphur dioxide emissions released in terms of kg/tons of coal were calculated using the following equation:

SO_2 per kg/tons of coal= average total sulphur as received × 20 ×sulphur conversion ratio

It should be noted the sulphur analysis is out of 100 and to make it per ton of coal it is multiplied by 10. Secondly sulphur has a molecular mass of 32 and SO_2 has a molecular mass of 64. Therefore S is twice the SO_2 by mass.

An air-dried sample of coal was used in order to determine the average inherent moisture. The formula for the average inherent moisture is:

Inherent moisture= Air dried sample – (Ash + Volatile matter + Fixed carbon)

= 100-(Ash+ Volatile matter +Fixed carbon) %

All the emission factors were then converted from kg/ton to tonnes using the following formulas:

Calculated SO_2 (tons) $\frac{average\ inherent\ moisture \times calculated\ SO2\ (kg/tons\ of\ coal)}{1000}$

The emitted sulphur dioxide emissions in tons were converted to g/s since AERMOD requires the emission factors to be in g/s.

SO_2 emissions (g/s) $= no\ of\ days\ in\ a\ months \times 24\ hrs \times 60\ min \times 60\ sec \times 1000000$

Nitrogen oxides emissions were calculated as nitrogen dioxide. The formulae used to calculate the nitrogen dioxide emissions are outlined below.

NO_x as NO (tons) $= \frac{units\ generated \times emission\ factor}{1000}$

The nitrogen oxides calculated as nitric oxide were then used to determine the amount of nitrogen dioxide emissions from Matimba power station.

NO_x emissions as $NO_2 = \frac{Nox\ as\ NO\ \ tons\ \times molar\ mass\ of\ nitrogen\ dioxide}{Molecular\ weight\ of\ NO}$

All the monthly values are displayed in a table below and were averaged into annual emissions in order to run the model.

Table 2. 3 Matimba power station's Gaseous emissions calculated as g/s in 2011 (Keir, 2011)

Months	**Coal burnt tons**	**Units generated GWh**	**Coal usage kg/GWh**	**Calculated SO_2 g/s**	**Calculated NO_x (as NO_2) g/s**
January	1095932	2061.0170	531743.31	9912.30	1891.00
February	1147412	2246.5250	510749.71	10222.90	2116.37
March	1268645	2322.6740	546200.20	10264.55	2261.98
April	1257123	2434.5190	516374.28	10106.09	2241.43
May	1483844	2559.7560	579681.81	11568.39	2560.33
June	1210660	2346.9750	515838.47	9733.16	2158.59
July	1189518	2356.3040	504823.66	9419.19	2052.48
August	1156582	2250.4210	513940.28	9274.21	1995.65
September	1436062	2456.2280	584661.52	11766.76	2560.48
October	1385244	2580.7760	536754.84	11434.64	2390.20
November	1240461	2334.1220	531446.51	10010.27	2211.72
December	1081914	1950.1580	554782.74	8682.19	1866.81
Total	**14953397**	**278990.4750**	**6426997.34**	**10166.40**	**2221.81**

Meteorological conditions as model inputs

AERMET, one of the pre-processors of AERMOD was used to calculate the hourly boundary layer parameters e.g. Monin-obukhov length, convective velocity scale, temperature scale, mixing height and surface heat flux. The parameters (Surface heat flux, Monin-obukuv length and etc.) calculated by AERMET are important in the evolution of the boundary layer which, in turn, influences the dispersion of pollutants.

The above-mentioned meteorological data was used to run AERMOD. Both the Climatology Research Group's database and the Eskom database were used to get surface characteristics, cloud cover, upper air temperature sounding and near surface measurement of wind speed within the study area. Longitudinal and latitudinal coordinates as well as the time zone and wind speed threshold were used as input to AERMET.

AERMET produced two files for input into AERMOD. The surface file contained observed and calculated surface observations. The profile file contained one level observation from an Automatic Weather Station (AWS) obtained from the South African Weather Services (SAWS).

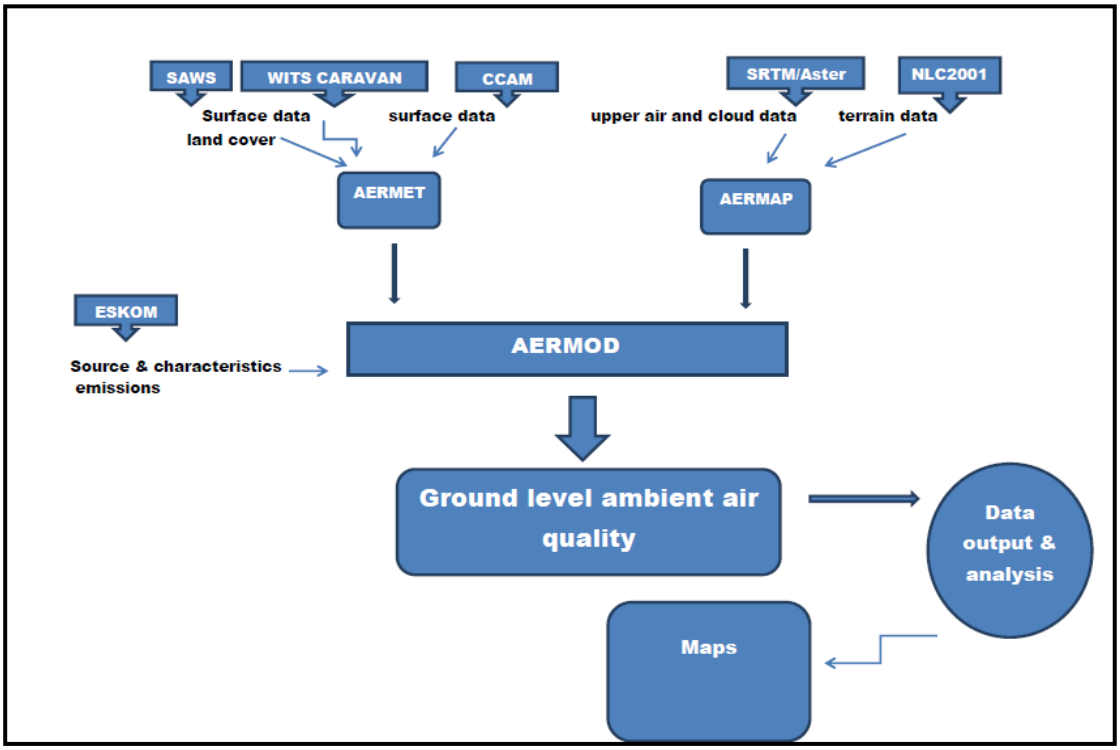

Figure 2. 3 A flow chart of the methodology showing all required data input and their sources as well as the end results which will be in the form of maps.

Elevation data as model input

AERMAP was used as a pre-processor in order to load the elevation data sets, and then AERMOD analysed the data. AERMAP required the use of gridded data to calculate terrain height scale for the receptor locations. The terrain data required by AERMAP was obtained from SRTM and land cover data was obtained from NLC2001 (Figure 2.3). AERMOD simulated a horizontal plume under stable conditions and also an elevation-following plume in order to account for varying elevation in the area.

All the necessary steps followed in order to acquire, ensure quality and analyse the monitoring data were highlighted in this chapter. The AERMOD model was briefly discussed and all the data required by the model were outlined. Monitoring results will be discussed in chapter three.

Chapter 3: Baseline conditions in Lephalale area

This section describes the ambient air quality data from the Grootstryd and Marapong monitoring stations. The data analysed is from the year 2005 till 2010. The monitoring data was analysed using diurnal variations, seasonal variations, wind roses and pollution roses.

Grootstryd monitoring results (2005-2006)

Grootstryd monitoring station is owned by Eskom and was in operation from January 2005 to August 2006. Of the pollutants under investigation SO_2 is the only one recorded at that station. Even though recording last took place in 2006 the results will be compared against the current ambient air quality national standards.

Sulphur dioxide concentrations recorded at Grootstryd monitoring station

Hourly mean concentrations of sulphur dioxide recorded at Grootstryd are above the current national standards (Figure 3.1).The total number of Exceedences recorded is 15. The highest value recorded is 206 ppb and it was recorded between March and April 2005.

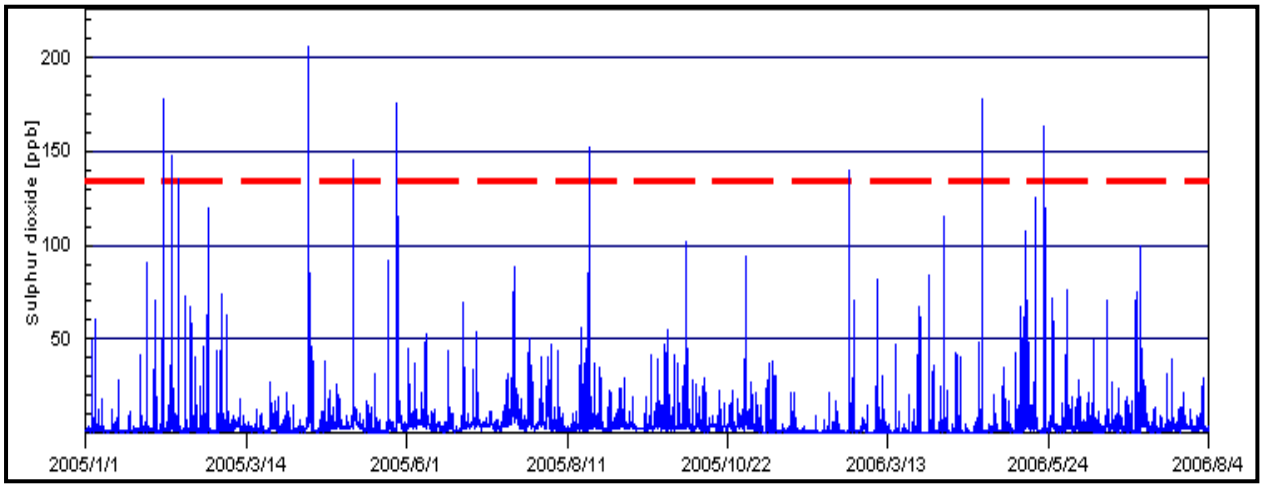

Figure 3. 1 SO_2 average hourly mean concentrations recorded at Grootstryd during the period January 2005-August 2006.

The sulphur dioxide daily mean concentrations recorded at Grootstryd (Figure 3.2) are below the national 24-hour ambient air quality standard. There are no Exceedences recorded and the highest concentration recorded is approximately 42 ppb. The highest concentrations were recorded around February 2005. When the daily mean average concentrations of 2005 are compared against the 2006 ones it can be noted that the pollutant followed no specific trend.

Based on the recorded results it was concluded that, from 2005 to 2006, there were no significant sulphur dioxide emissions above the current national standards. Based on this research, it can be safely said that sulphur dioxide emissions were not a problem in Lephalale in 2005-2006 in the areas in close proximity to the Matimba power station.

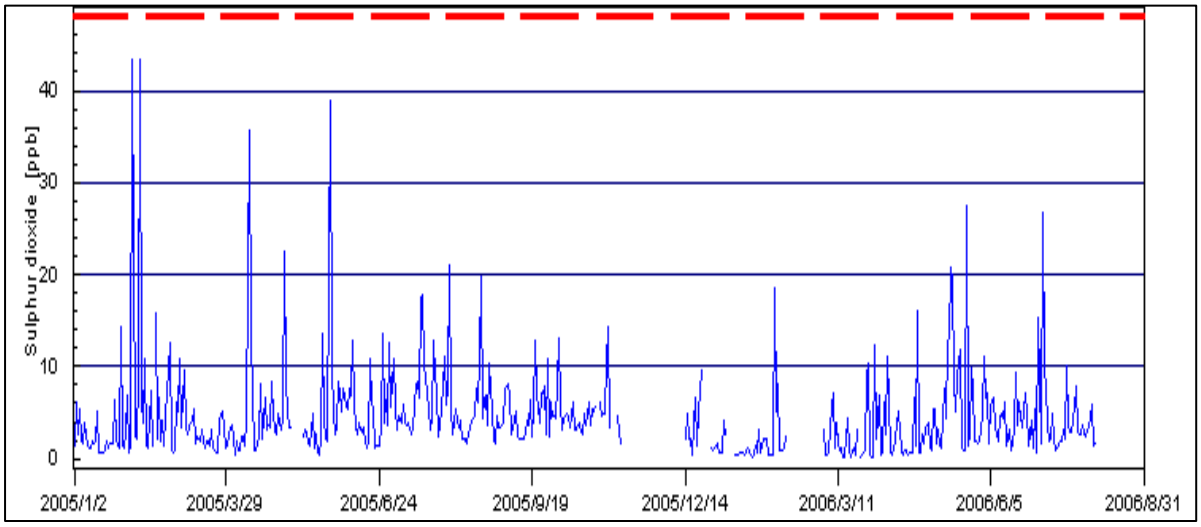

Figure 3. 2 Sulphur dioxide daily mean concentrations recorded during the period January 2005-August 2006. The red dotted line indicates current national standard

Sulphur dioxide and Wind speed diurnal variations observed at Grootstryd

A direct relationship between wind speed and sulphur dioxide diurnal variations are noticed when comparisons are made (Figures 3.3 and 3.4). When the wind speed is high, sulphur dioxide concentrations are also high. Higher sulphur dioxide concentrations are recorded between the 9^{th} and the 17^{th} hour of the day.

Emissions associated with tall stacks are expected to have a significant impact at ground level between 09:00 and 16:00 due to atmospheric turbulence influences. During the evening and early morning time, low-level sources are expected to impact the ground due to temperature inversion. It is clear that the highest values recorded are associated with tall stacks. From the recorded results it is evident that, even when those values are high, they are not above the national ambient air quality standards.

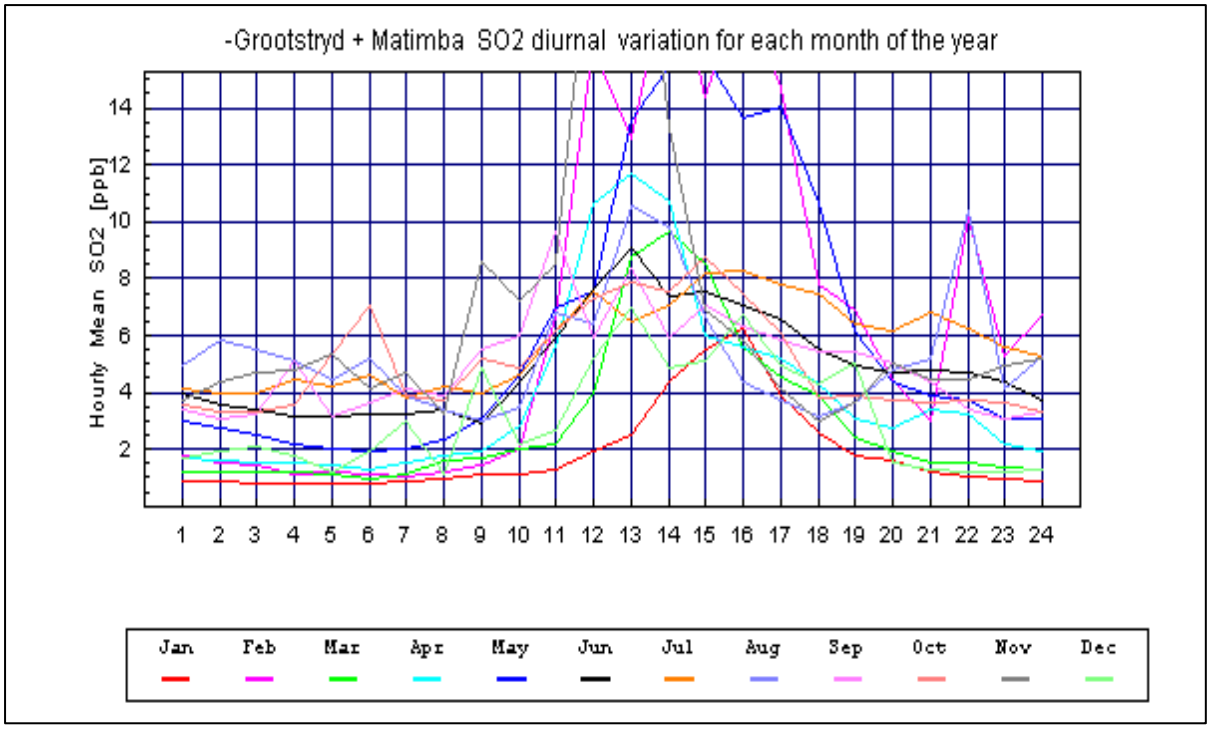

Figure 3. 3 SO_2 diurnal variations for each month of the year at Grootstryd (2005-2006)

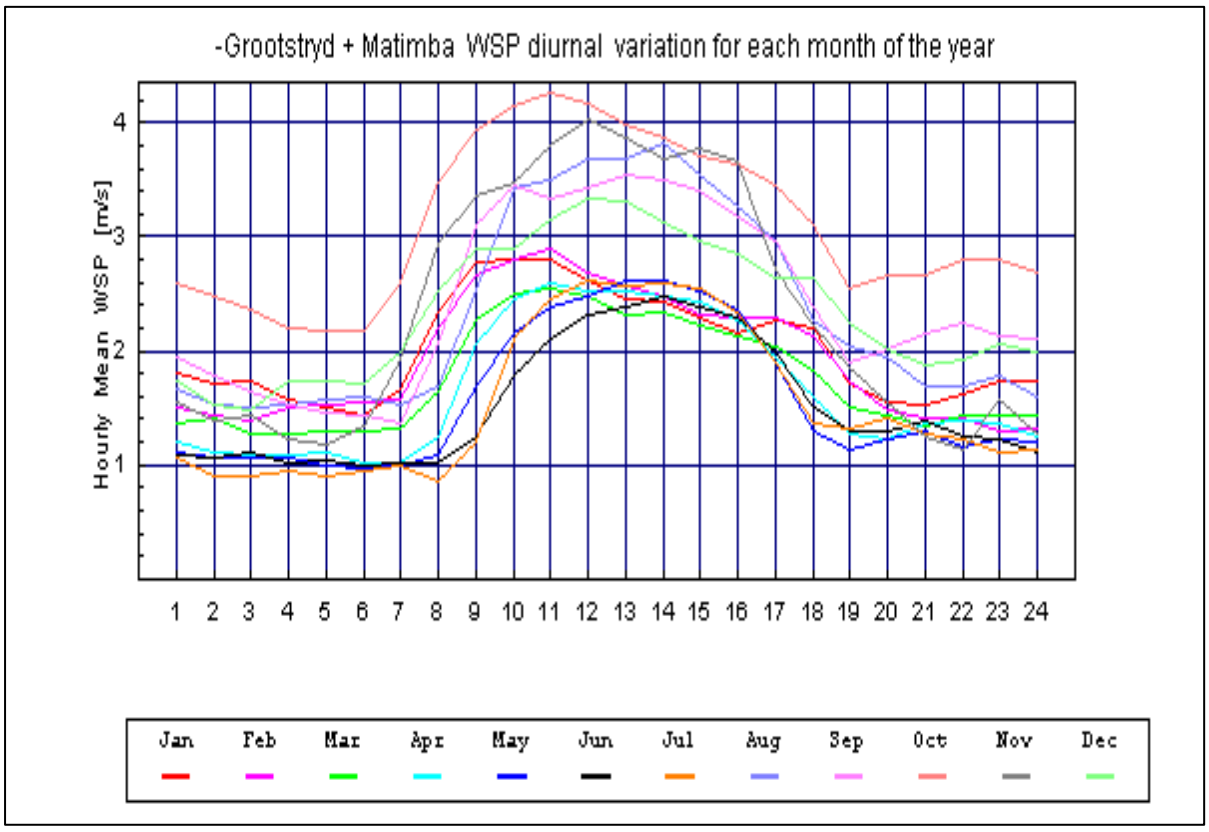

Figure 3. 4 Wind speed diurnal variations for each month of the year recorded at Grootstryd monitoring station January 2005-August 2006

Sulphur dioxide seasonal variations at Grootstryd

The months of June (winter) and February (summer) were chosen to assess the influence of seasonal variation at Grootstryd monitoring station. The year 2005 was chosen because, in comparison to the year 2006, data recovery was high for February and June. The graphs (Figure 3.4 and 3.5) show similar trend during the summer and winter. The highest values were recorded during summer because turbulences are expected to be high. In winter calm conditions are experienced and the surface inversion layer is broken late due to less radiation. Higher values were experienced late in the afternoon between 12:30 and 17:00 which is a typical signature of tall stacks (Figure 3.4 and 3.5). When compared with the hourly standard no exceedences were found. During summer the highest peak was recorded at 13:00, and the other peaks were recorded at 15:00 and 17:00. The wind sector at 13:00 is between NNE and ENE direction which indicate that the power station has an influence on the high SO_2 recorded. At 15:00 the peak recorded was between the NE and ENE sector which also shows the influence of the power station. The peak recorded indicated two sources - one form the ENE sector -which is most likely to be the power station. The other source was from the ESE sector and could not be identified. The results indicate that the power station influences the ground level concentrations recorded at Grootstryd.

During winter the highest peak recorded was at 16:00 and the concentration was 45 ppb. Other smaller peaks were recorded at 13:00 and 23:00. The peak recorded at 13:00 between the North-northeast (NNE) and East-northeast (ENE) sector was similar to the peak recorded during summer. The value recorded was far lower than the one recorded in summer. At 16:00, the peak was influenced by sources from the Northeast (NE) to ENE and also from the West-northwest (WNW) to Northwest (NW). This indicates that the power station and another source from the WNW-NW direction were responsible for that peak concentration. During the evening at 23:00, the major wind sector recorded was Southwest (SW) to West-Southwest (WSW) which indicates that the emissions of sulphur dioxide at that time are not from the power station. At that time of the evening the diurnal signature is expected to be that of ground level sources. It is evident that higher values are recorded during summer season when there is more turbulence. This causes high ground level concentrations.

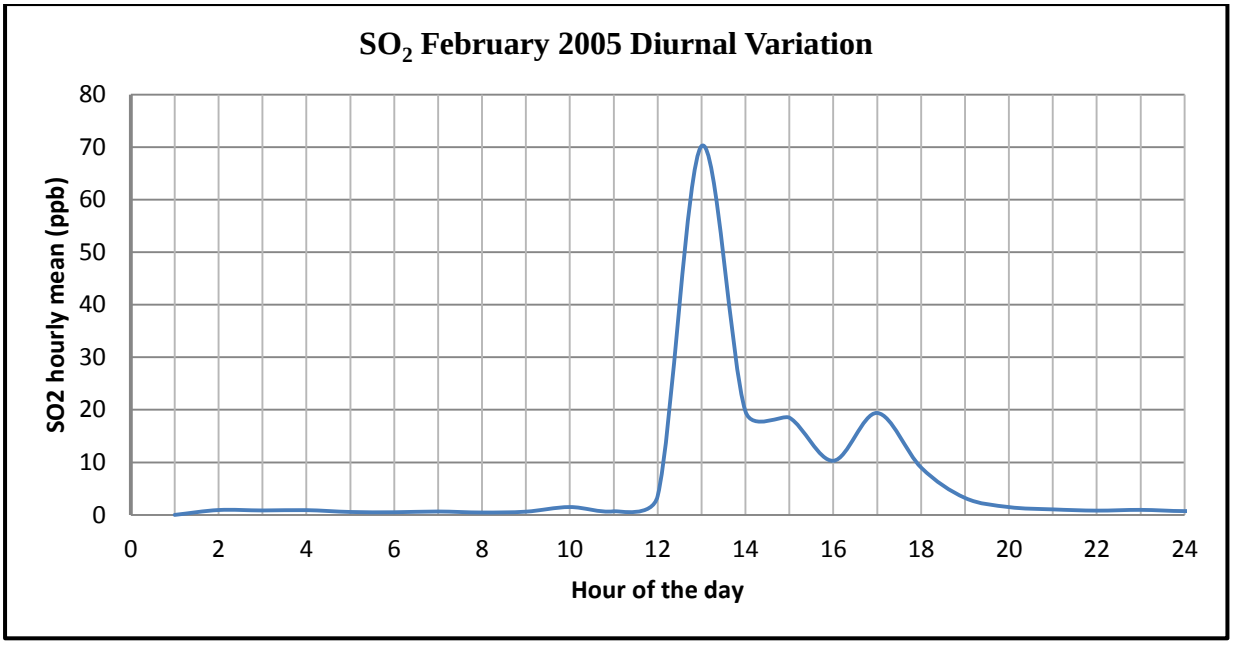

Figure 3. 5 Grootstryd sulphur dioxide diurnal variation during February 2005

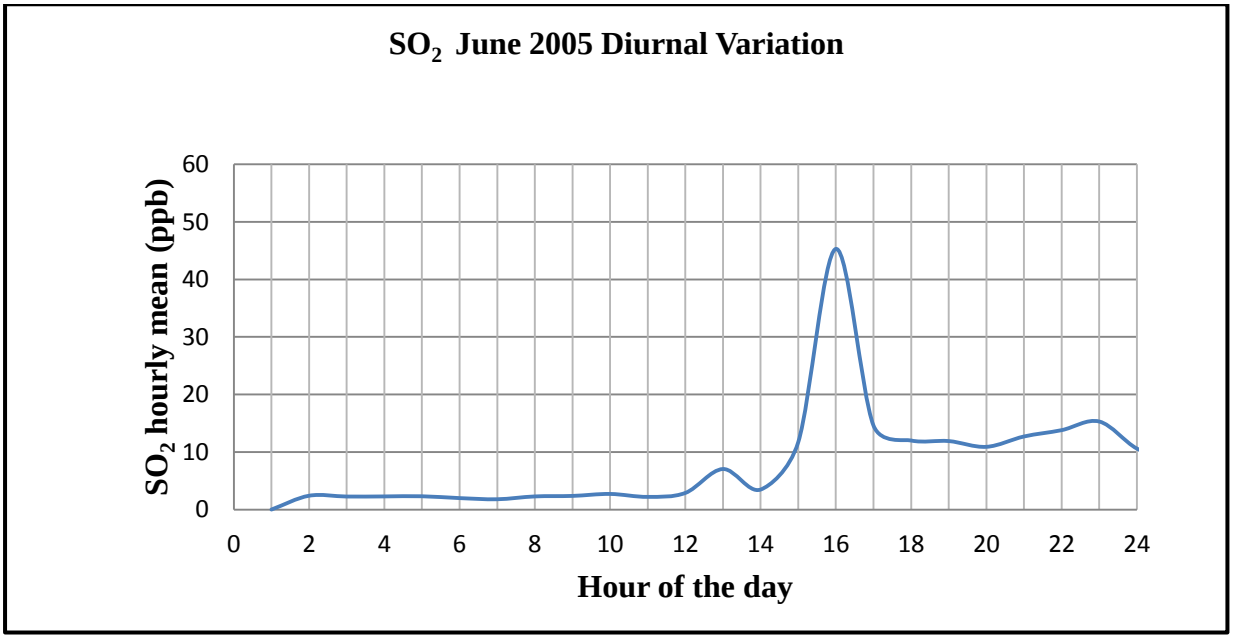

Figure 3. 6 Grootstryd sulphur dioxide diurnal variation during June 2005

Wind speed and pollution roses recorded at Grootstryd for the period 2005-2006

In Lephalale, the proportion of calm winds was only for 7.4 % throughout the day (Figure 3.5). A higher proportion of calm winds were experienced during the night. This is supported by a diurnal variation in wind speed (Figure 3.4) where low wind speeds are experienced from 19:00 to 07:00. The dominant wind direction during the day is from the north eastern side whereas the dominant wind direction is from the eastern side during the night.

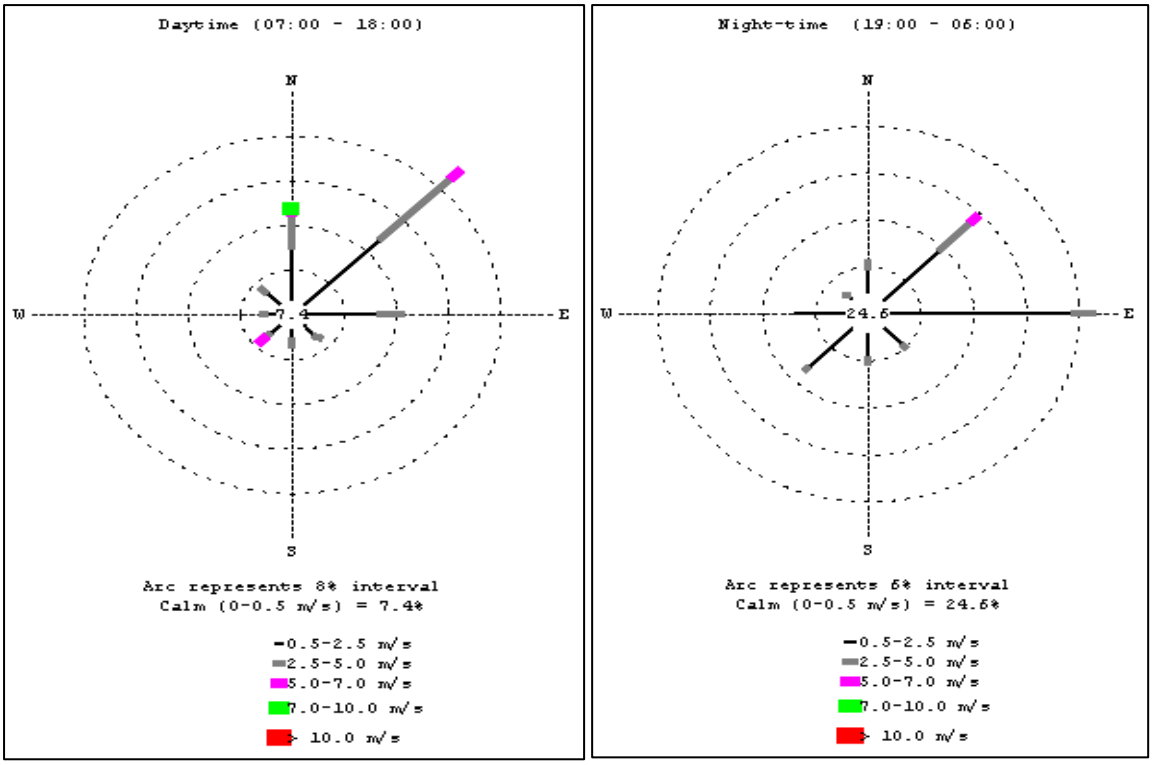

Figure 3. 7 Day and night time wind roses in Lephalale observed at Grootstryd from 2005-2006

Throughout the day the dominant wind blows from the east (E), ENE, NE and NNE (Figure 3.7). High wind speeds are associated with high sulphur dioxide concentrations (Figures 3.6 and 3.7). The highest concentration recorded is greater than 48 ppb from dominant wind directions. The pollution rose diagram (Figure 3.8) also supports the results recorded by the diurnal variations. Most of the pollutants shown by the pollution roses diagram are between the NNE and the ENE sectors. From the diurnal variations in all seasons the dominating wind direction for all the peaks recorded was between NNE and ENE. Such wind sectors are responsible for dispersing the pollutants from Matimba power station to the monitoring-site and surrounding areas.

Marapong Monitoring results (2007-2010)

Marapong monitoring station is also owned by Eskom. Of all the pollutants under investigation it only records SO_2 and NO_x. It is situated on the South-eastern side of the Matimba power station. The monitoring station was located at that area in order to monitor the impact of the Matimba power station on the Marapong Township. It was located there when the NEM: AQA, 2004 (act 57 of 2004) was promulgated. It shifted from a source-based approach to a receptor-based approach.

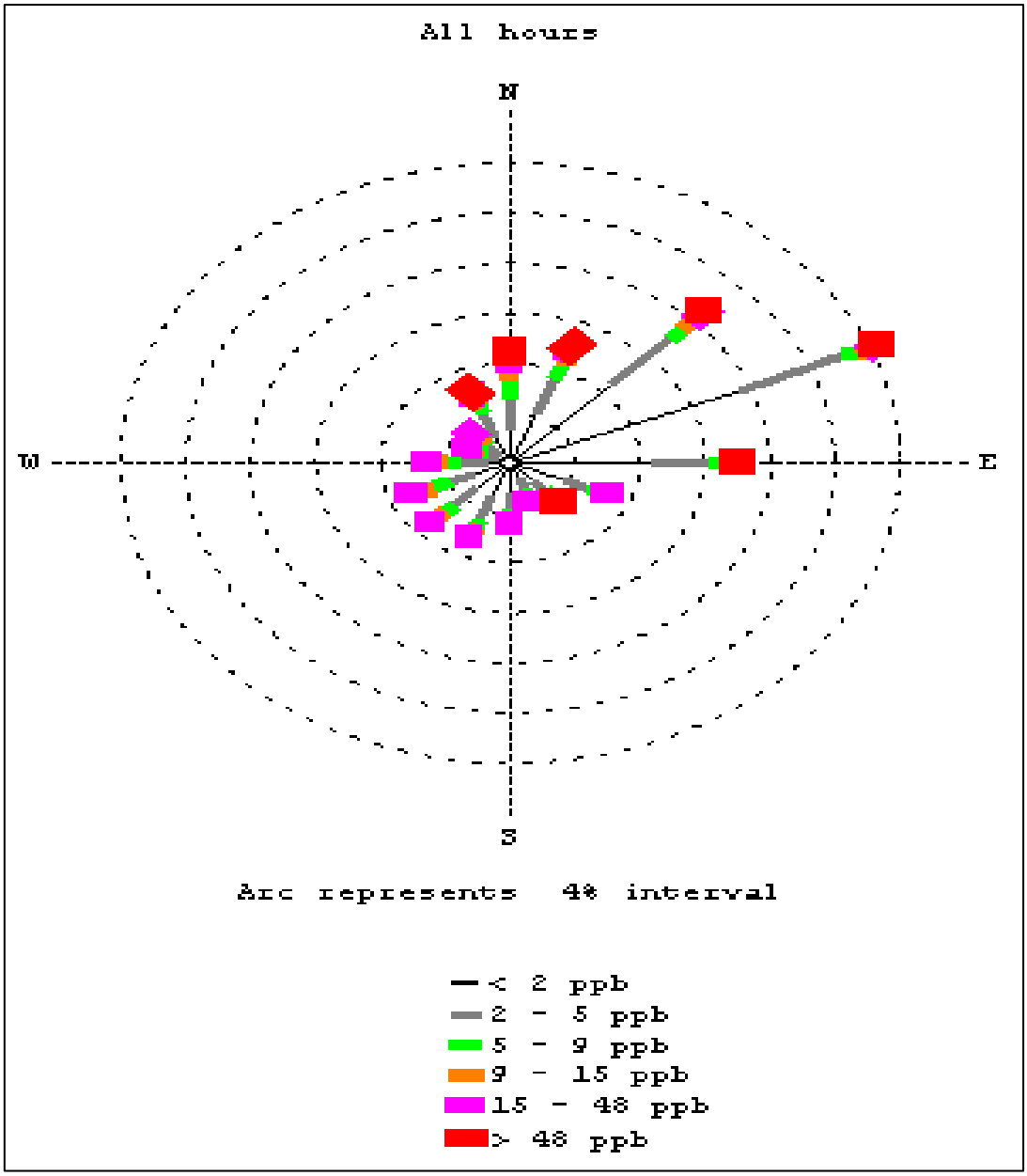

Figure 3. 8 Pollution roses for Lephalale recorded at Grootstryd during the period January 2005-August 2006

Sulphur dioxide concentrations recorded at Marapong monitoring station

Sulphur dioxide daily mean concentrations recorded at Marapong are above national standards. Only eight Exceedences where recorded from the period of 2007-2010 (Figure 3.9). The allowed Exceedences for hourly averages are four. Daily mean concentrations recorded from the period of 2007-2010 are below national standards. The highest recorded daily mean concentration recorded is 46 ppb (Figure 3.10) whereas the highest daily mean concentration is 180 ppb. The above-recorded monitoring results indicate that sulphur dioxide emissions have not been a cause of concern within the vicinity of the power station. It should

also be noted that the Marapong monitoring station is located within a township where other community activities contribute to sulphur dioxide emissions. The recorded results therefore show compliance.

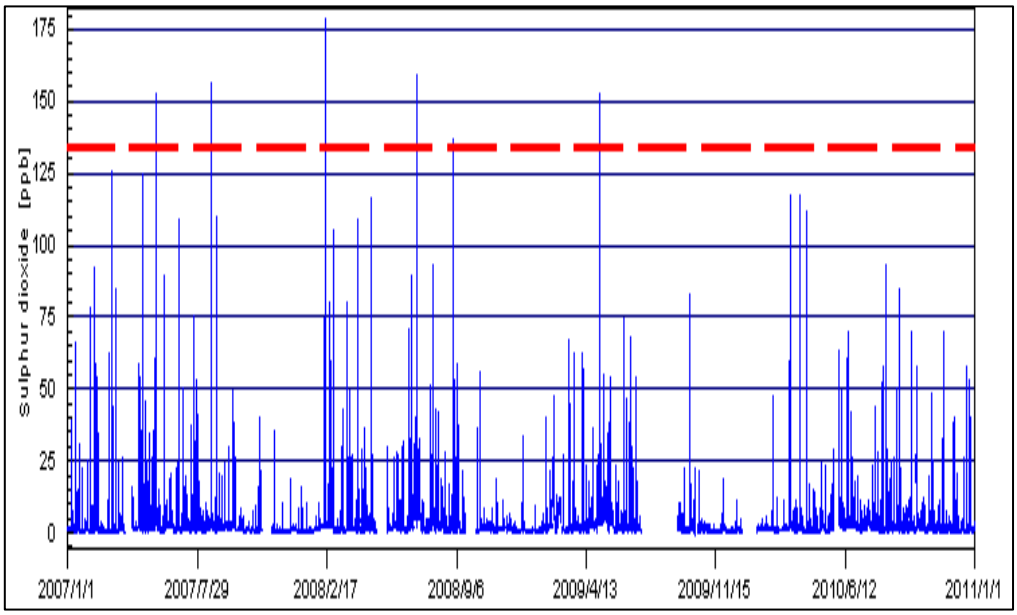

Figure 3. 9 SO_2 hourly mean concentrations during the period of 2007-2010 recorded at Marapong monitoring station.

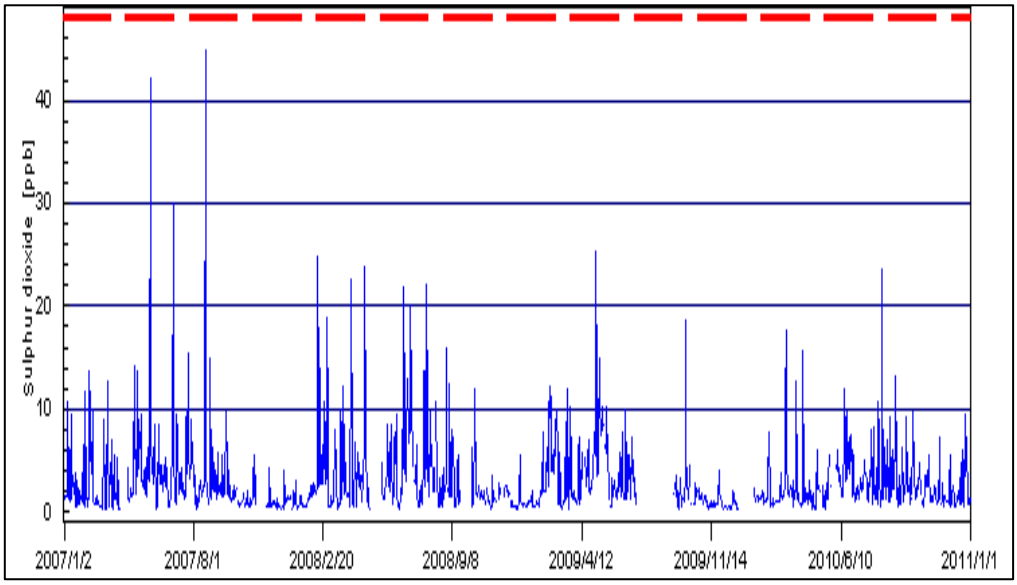

Figure 3. 10 SO_2 daily mean concentrations during the period 2007-2010 recorded at Marapong monitoring station.

Nitrogen oxide concentrations recorded at Marapong monitoring station

There are currently no standards on nitrogen oxides. When nitrogen oxides hourly mean concentrations are compared with sulphur dioxides hourly mean concentrations, it is evident that nitrogen oxides are higher than sulphur dioxides (Figure 3.11). From 2007 till 2010 there was an increase in the NO_x concentrations recorded at Marapong.

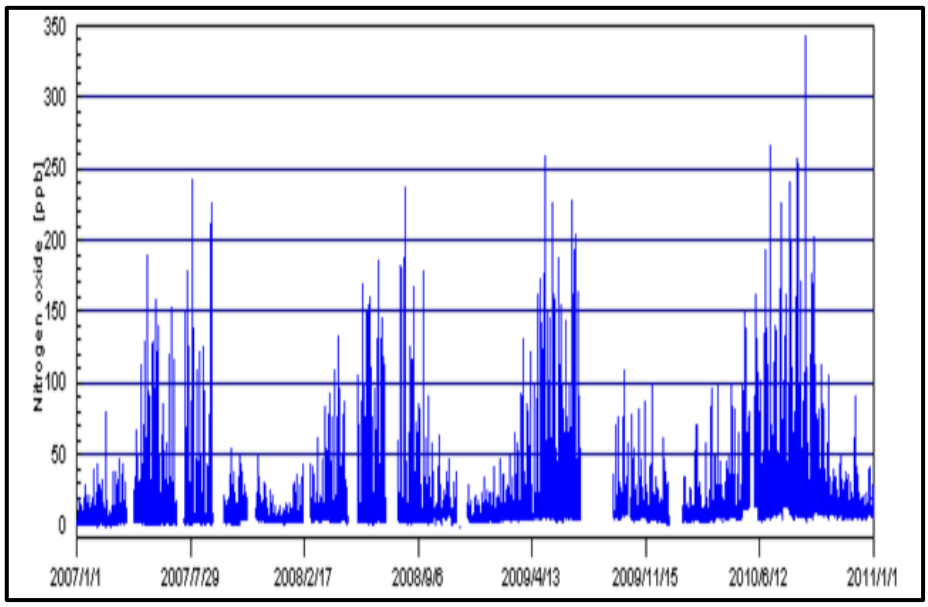

Figure 3. 11 NO_x hourly mean concentrations for the period of 2007-2010 recorded at Marapong monitoring station

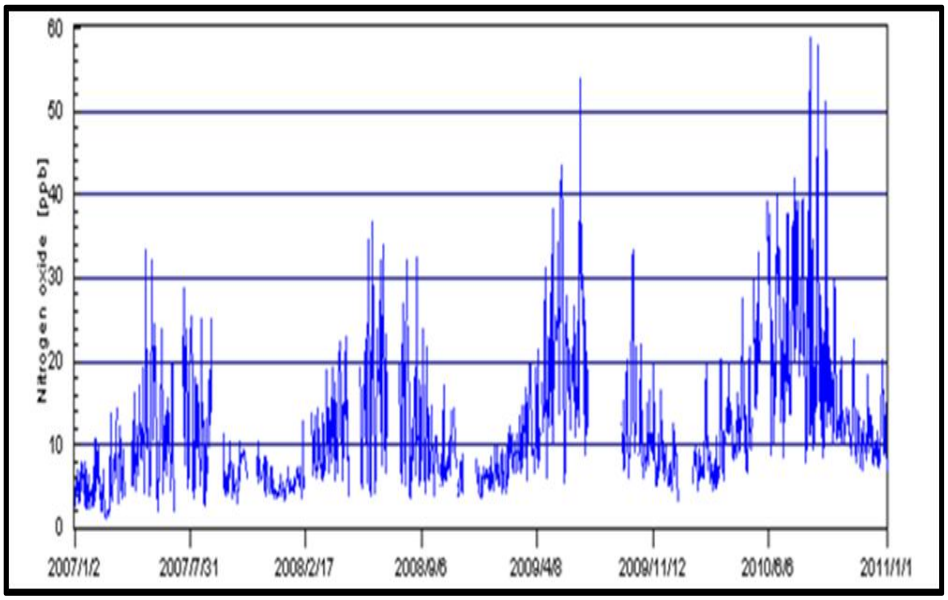

Figure 3. 12 NO_x daily mean concentrations for the period of 2007-2010 recorded at Marapong monitoring station

Comparison between sulphur dioxide and nitrogen oxide at Marapong

The wind speed is higher in the Marapong area from 09:00 till 18: 00 and at its lowest peak during the early morning (Figure 3.13).NO_x concentrations are higher than the SO_2 concentrations in all hours of the day. NO_x concentrations are at their peak from 6:00-9:00 with a decline and rise from 19:00-21:00. Such peaks are not associated with tall stacks but rather with low-level sources.

The differences between the NO_x and SO_2 diurnal signatures also show that they are from different sources. This is supported by the scatter plot that shows no relationship between sulphur dioxide and nitrogen oxides (Figure 3.15). The R^2 value indicated by the linear regression diagram (Figure 3.16) indicates that there is no correlation between sulphur dioxide and nitrogen oxides. These results prove that the two pollutants come from two different sources.

Tall stacks are expected to have a significant impact on the ground from 9:00-16:00. From the graph it is evident that power stations have no impact on the area when it comes to nitrogen oxides. The SO_2 concentrations in the area are fairly low. The rise from 12:00-18:00 was still below the national hourly standards. Based on this research, it can be safely said that the power station in the area does not emit significant amount of sulphur dioxide and from the diurnal variation graphs it can be noted that the SO_2 concentrations are not only from the power station.

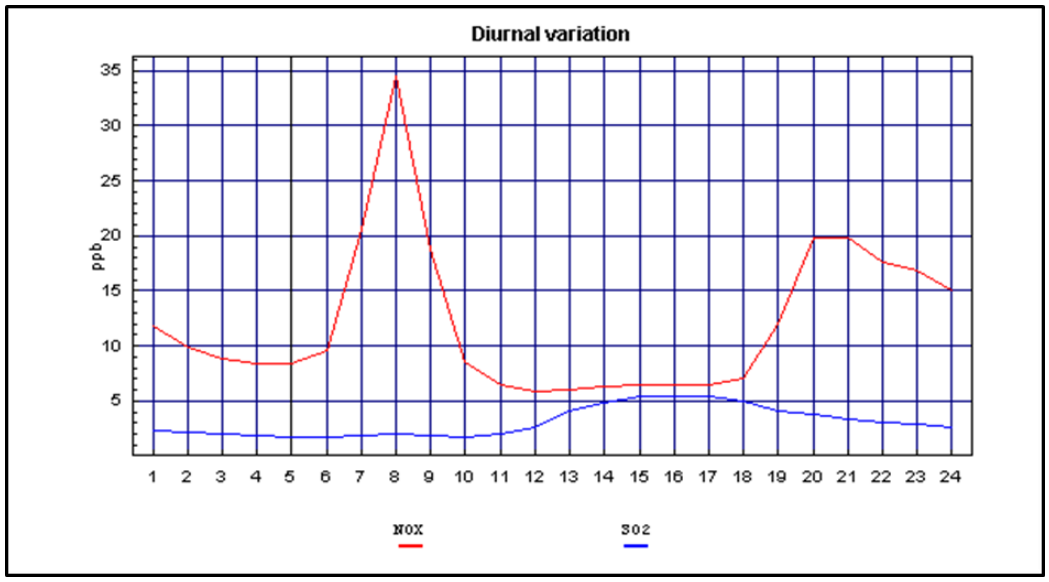

Figure 3. 13 Diurnal variations of SO_2 and NO_x for the period of 2007-2010

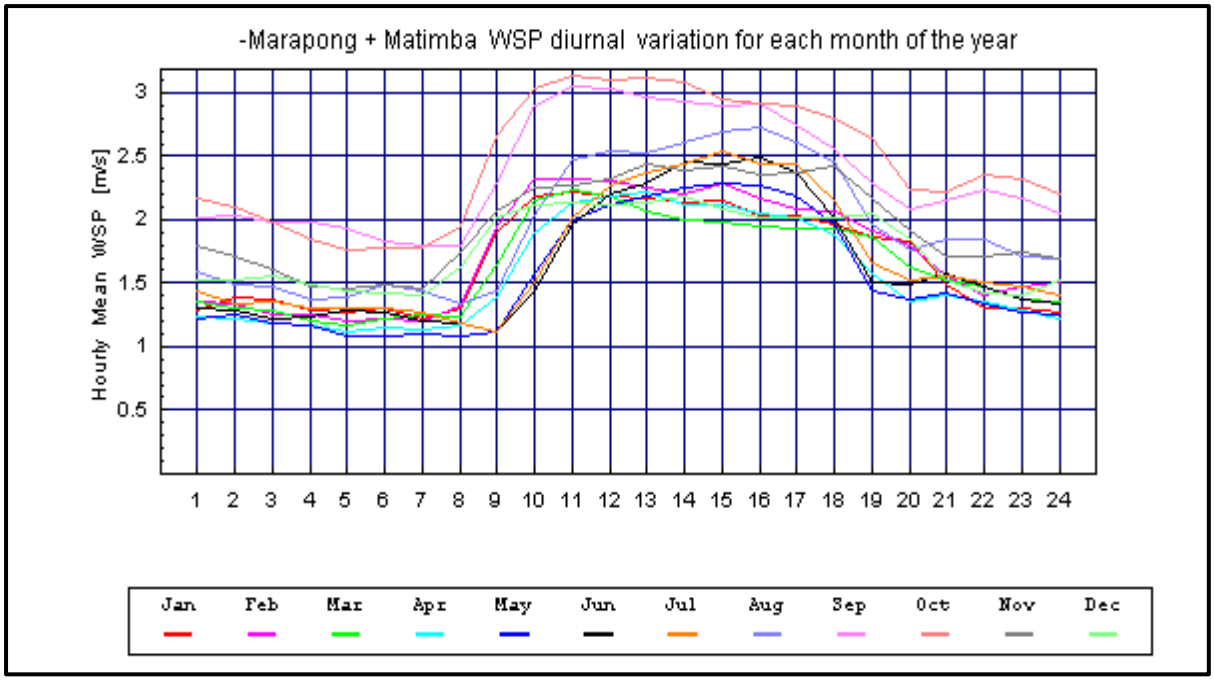

Figure 3. 14 Wind speed diurnal variations for each month of the year 2007-2010

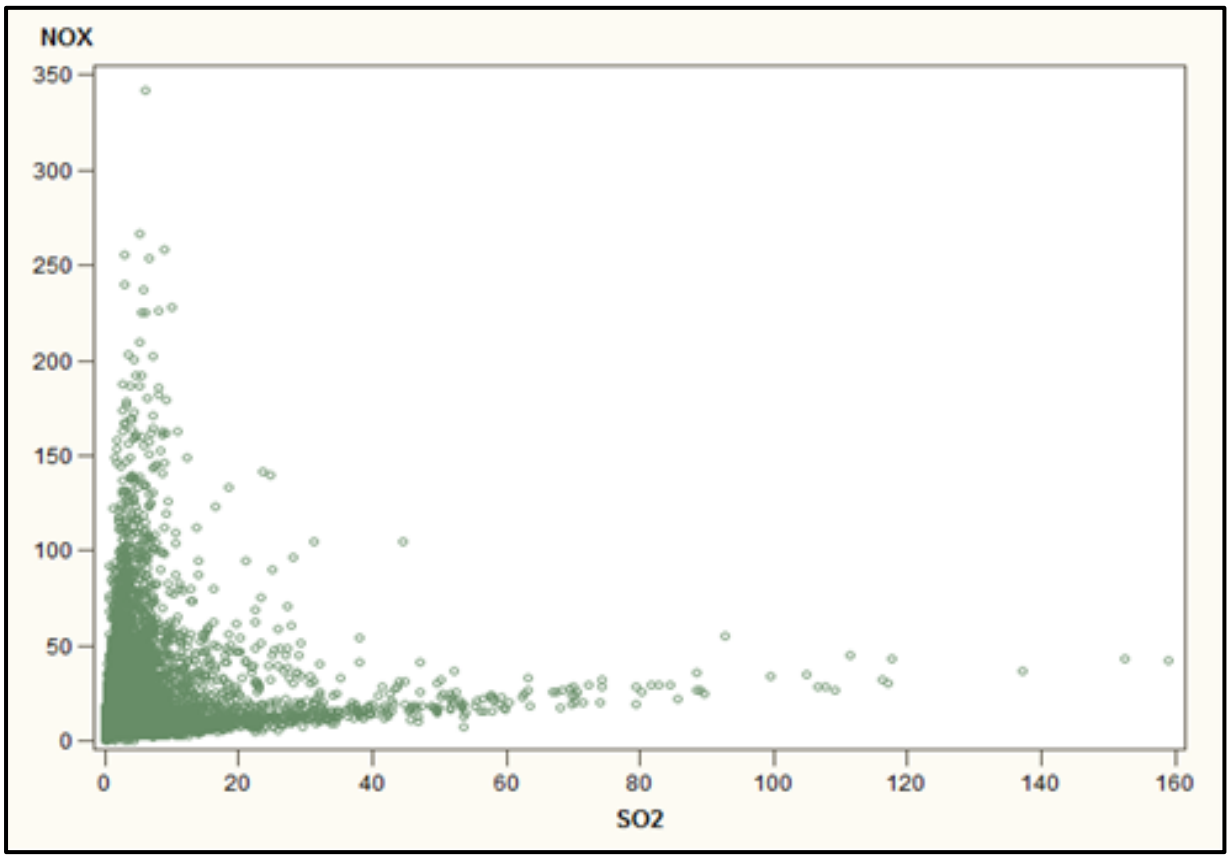

Figure 3. 15 Scatter plot for sulphur dioxide and nitrogen Oxide for the period 2007-2010 as recorded at Marapong monitoring station.

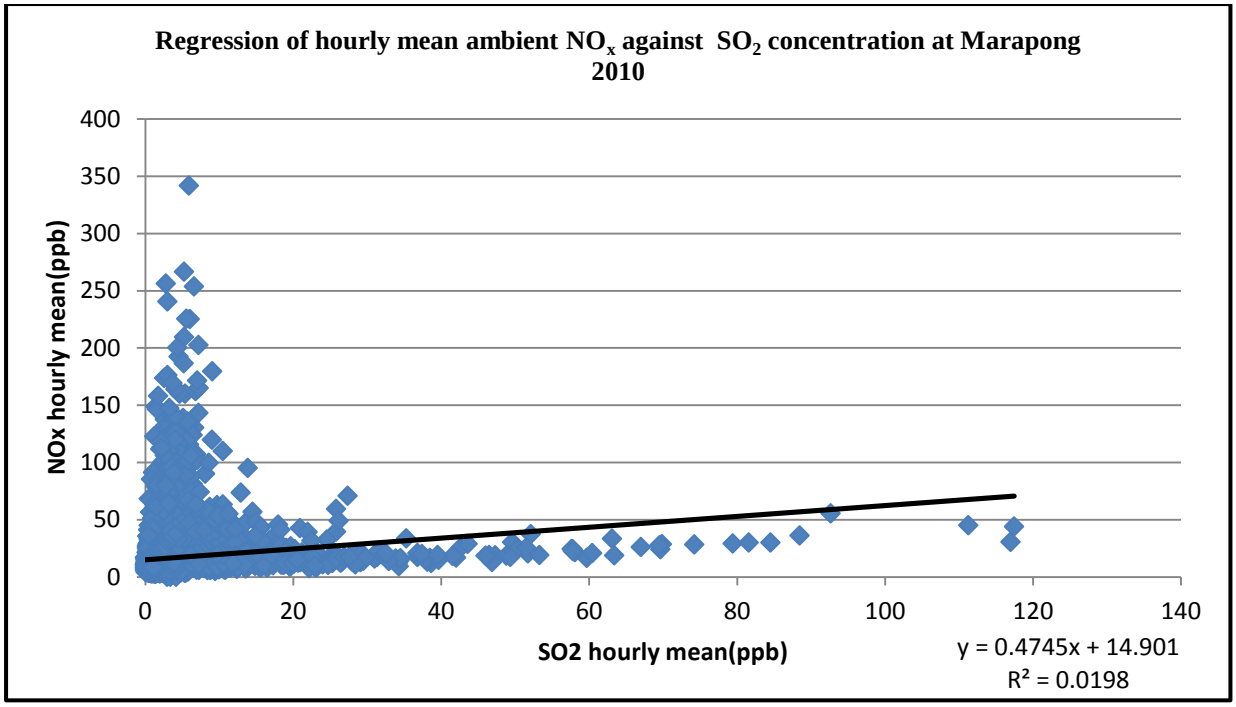

Figure 3. 16 Overall SO_2/ NO_x correlation at Marapong monitoring station

Sulphur dioxide seasonal variations at Marapong 2010

The months of June and February were chosen to assess the influence of seasonal variation at the Marapong monitoring station. The year 2010 was chosen because when the year 2010 was compared to the year 2008 and 2009, the data recovery for the months of February and June was high. The sulphur dioxide diurnal variations graph (Figure 3.17 and 3.18) shows a typical low-level sources signature. The concentrations are very low during both winter (June) and summer (February).

The highest concentration recorded in summer is 6 ppb. It was recorded at 20:00 between the ESE and SE sector which shows that it is not from the power station. Two peaks were recorded in winter at 2:00 (60 ppb) and 7:00 (20 ppb). These peaks do not show a typical diurnal signature for tall stacks emissions. At 2:00 the dominating wind sector was SE and SSE which is not in alignment with the direction of the power station. Such emissions can be from the township. During the early morning at 7:00 the source of the high ground level was from the SSW and WSW directions which could also be from an unidentified source. The signature shown by these graphs is mainly influenced by the location of the monitoring station. The monitoring station is located on the south-eastern side of the Matimba power station. However, the dominant wind direction is from the north-eastern side of the power station.

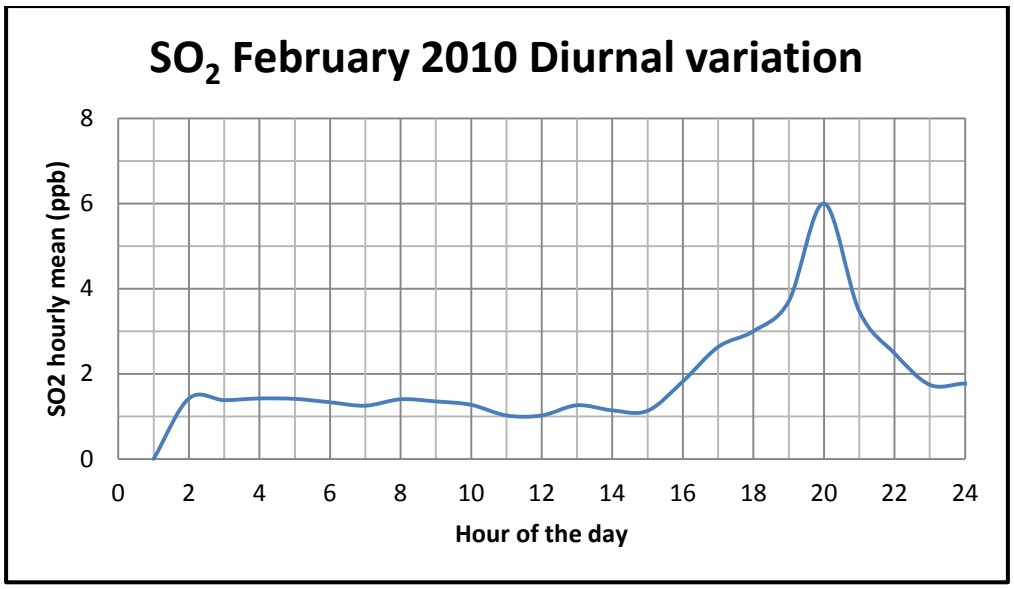

Figure 3.17 February 2010 sulphur dioxide diurnal variation recorded at Marapong monitoring station.

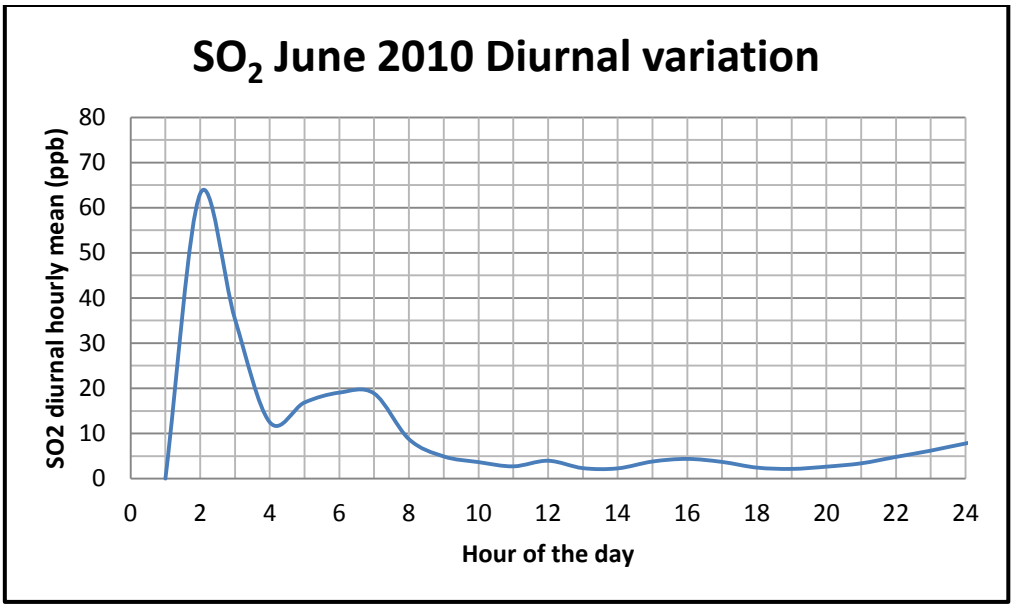

Figure 3.18 June 2010 sulphur dioxide diurnal variation recorded at Marapong monitoring stations

Comparison between nitric oxide and nitrogen dioxide diurnal variations

The average diurnal variation concentrations of nitric oxide and nitrogen dioxide follow a similar trend (Figure 3.19). The peak concentrations for both nitric oxide and nitrogen dioxide are recorded at 8:00 in the morning. Another peak is recorded between 20:00 and 21:00 in the evening. Higher concentrations recorded at those times are not related to a

signature from tall stacks. The higher peaks recorded during the night are likely to be from ground level sources as emissions from ground level sources get trapped in the night time inversion layer where there is a high level of stability. Consequently dispersion is limited and high ground level concentrations are recorded. The peak recorded at 8:00 could be from near ground level sources as it is still too early for significant turbulence to have built up.

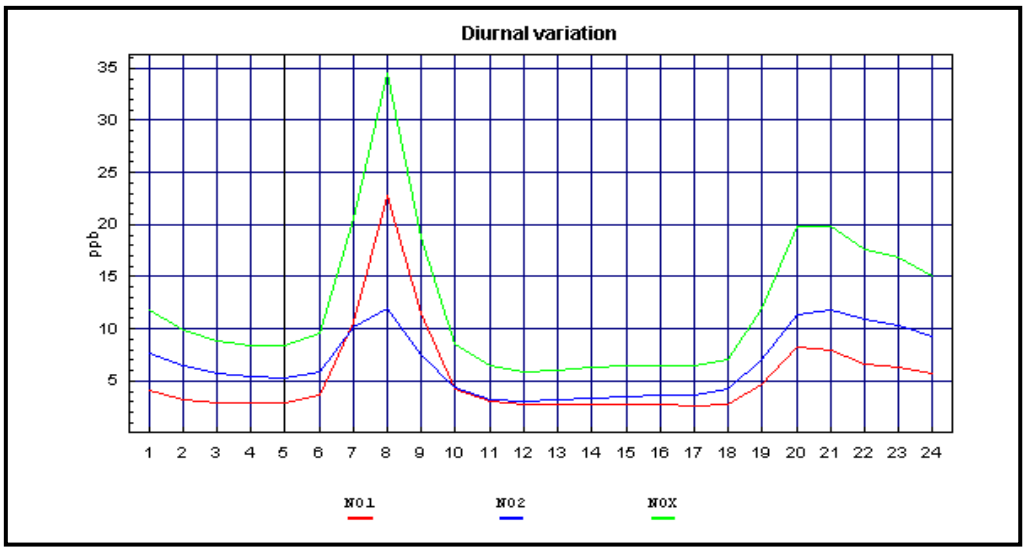

Figure 3. 19 Nitric oxide, nitrogen dioxide and nitrogen oxides diurnal variations for the period of 2007-2010

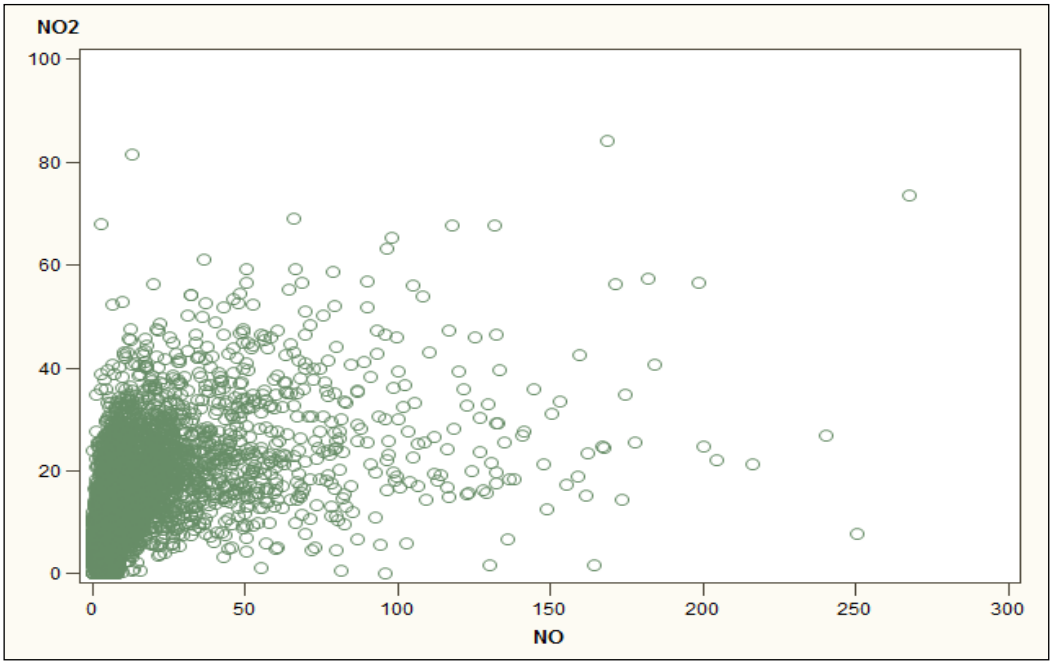

Figure 3. 20 Scatter plot to show the relationship between NO and NO_2 recorded at Marapong during 2007-2010

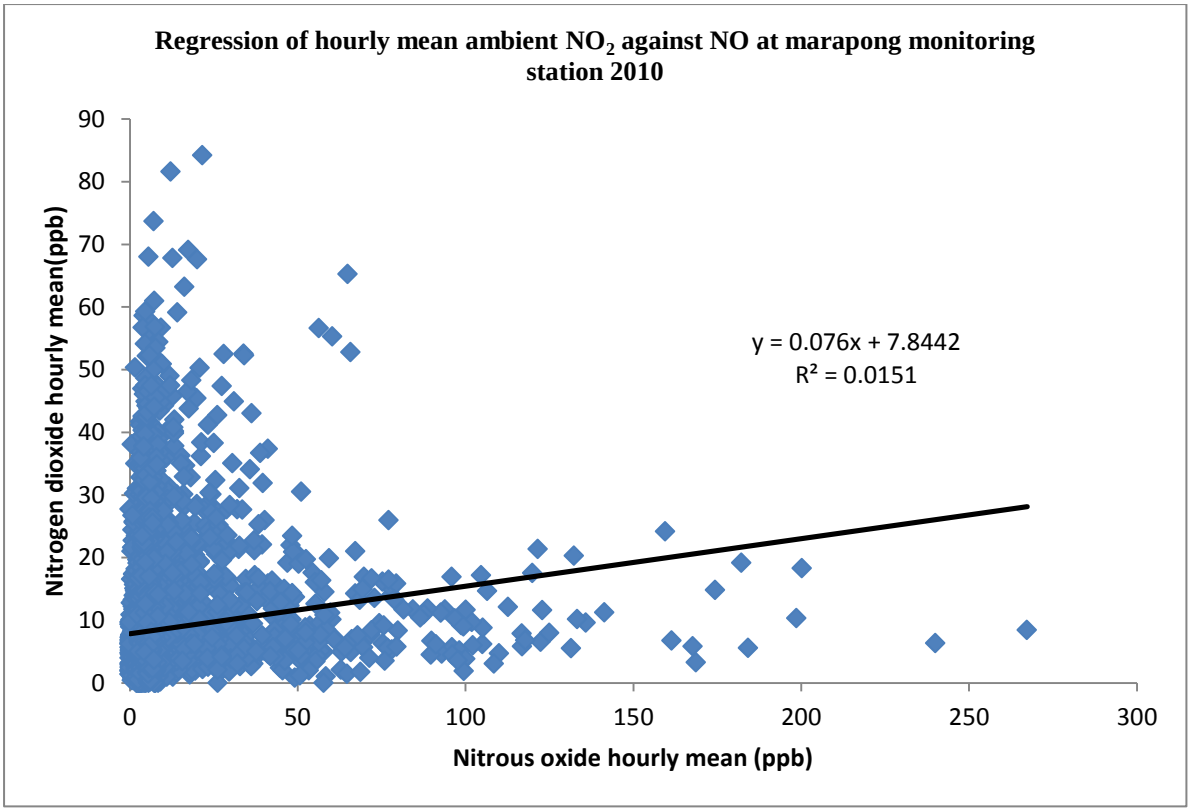

Figure 3. 21 Overall NO/ NO_2 correlation at Marapong monitoring station

When the concentrations of nitric oxide (NO) and nitrogen dioxide (NO_2) are compared, NO_2 is lower than NO during the morning. NO becomes lower than NO_2 in the evening. This trend is due to NO_x from both the power stations and other sources being largely released as NO. Hence NO_2 gets formed in the atmosphere when NO reacts with O_3. In most cases the NO_2 reactions are expected to decline during the day due to photo chemical reactions that take place. Diurnal variation for NO_x at Marapong (Figure 3.17) also follows a similar trend and during the evening NO_2 concentrations rise again.

The rise of NO_2 during the evening can be attributed to the reason that in the evening the atmosphere is characterised by stable conditions and there is also no solar radiation, hence a lack of vertical mixing. Consequently no photochemical reaction occurs and this results in a build-up of NO_2. When there is no photochemical reactions; chemical NO_x removal is eliminated and the end results in high concentration of NO_x near the surface levels. Higher values of NO_x result in removal of Ozone and this result in more NO_2 near ground level concentration recorded in the evening. This observation is supported by the linear regression model (Figure 3.21). The R^2 value is far from reaching one (0.0151). The scatter plot shows no specific association between NO and NO_2. R^2 value indicates that there is no linear

relationship between NO_2 and NO. This is expected since it indicates that the formation of NO_2 formation relies more on the photolytic reaction than the presence of NO.

Nitrogen oxides seasonal diurnal variations at Marapong

The months of June and February were chosen to assess the influence of seasonal variation at Marapong monitoring station. The year 2010 was chosen because when it was compared to the year 2008 and 2009, the data recovery for the months of February and June was high. During summer (February) (Figure 3.22) higher peaks were observed at 2:00 (11.9ppb), 09:00 (26 ppb), 16:00 (15ppb), 20:00 (12.2ppb) and 22:00 (17 ppb), whereas the peaks observed during winter (June) (Figure 3.23) were at 2:00 (35 ppb), 5:00 (33 ppb), 8:00(25 ppb), 14:00 (30 ppb) and 16:00 (90 ppb) . All the peaks recorded during summer were between East-southeast (ESE) and Southeast (SE) except at 22:00 when the direction of sources was from a wider range between ESE and South-southeast (SSE). Such directions do not support the power station as a source. During the winter the highest concentrations were recorded from the SE to South-southwest (SSW) sector except at 14:00 when the dominating sector was E-ESE sector. The SE-SSW sector indicates that the power station has an influence on the high ground level concentrations recorded at Marapong. The higher peaks from the SE-SSW are not only from the township but also from the power station.

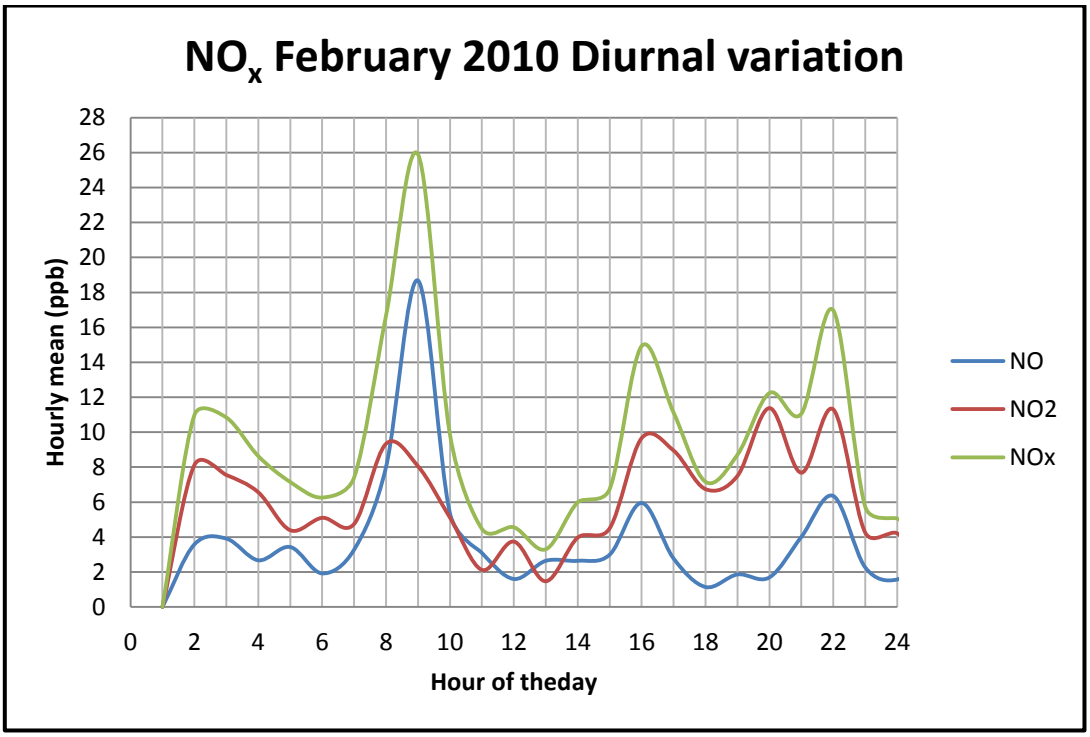

Figure 3.22 NO_x diurnal variations recorded at Marapong monitoring station February 2010

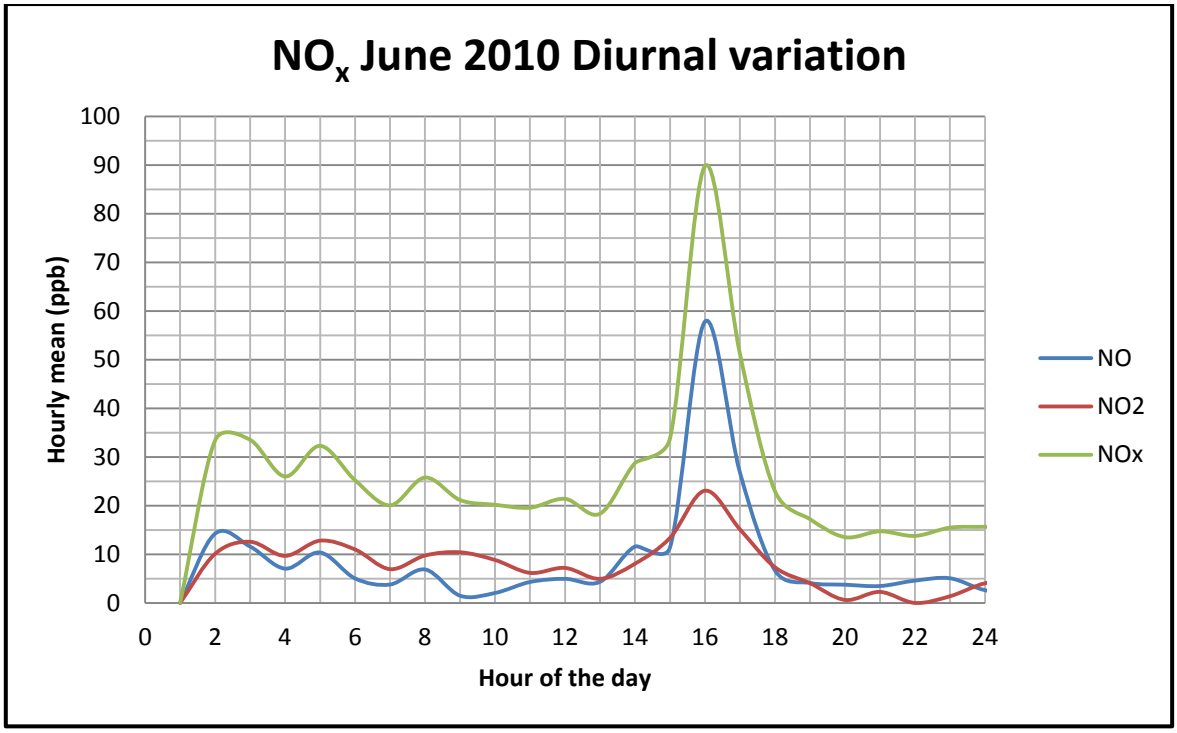

Figure 3. 23 NO_x diurnal variations recorded at Marapong monitoring station June 2010

Wind speed and pollution roses recorded at Marapong 2007-2010

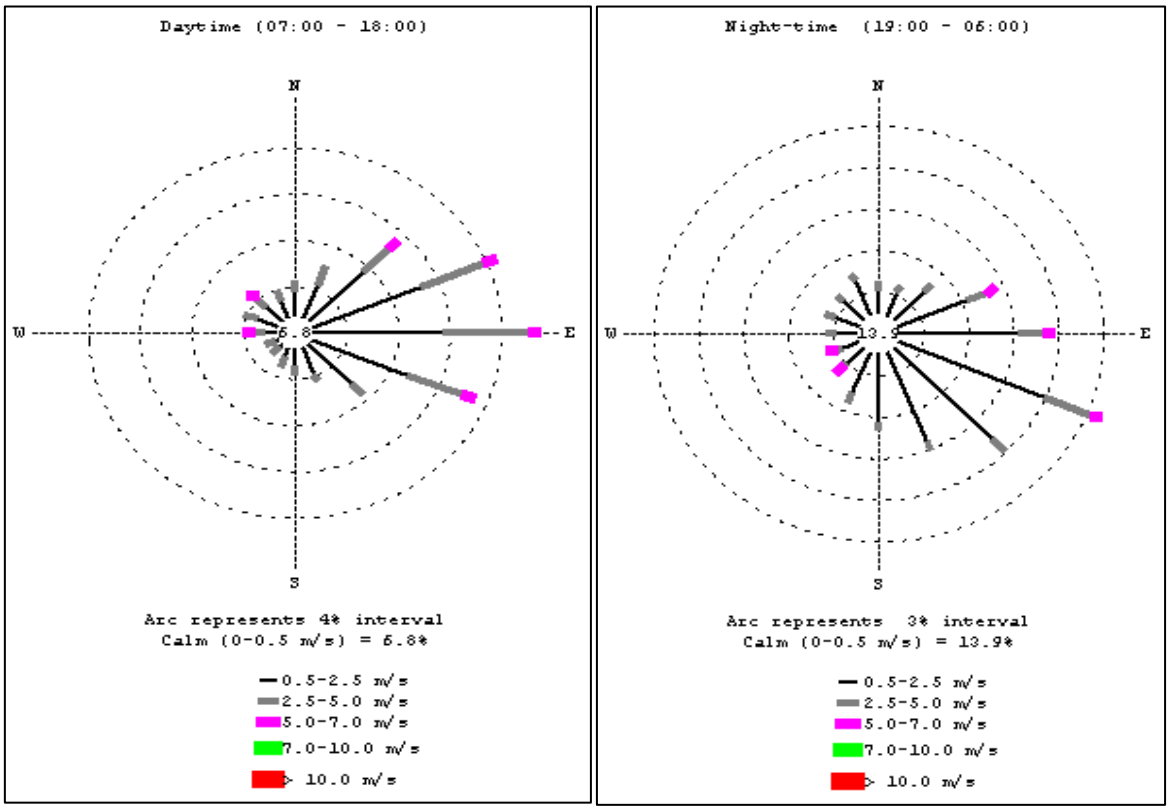

Figure 3. 24 Day and night wind roses in Lephalale observed from Marapong during the period 2007-2010

In Marapong calm winds are experienced throughout the day and night. They are more prevalent during the night (Figure 3.24). The highest recorded wind speed is between 5.0-7.0 m/s. During the day, the wind primarily blows from E, NE, NNE, ENE, and SE. During the night the dominant wind directions are SE, SSE, ESE, E and NE.

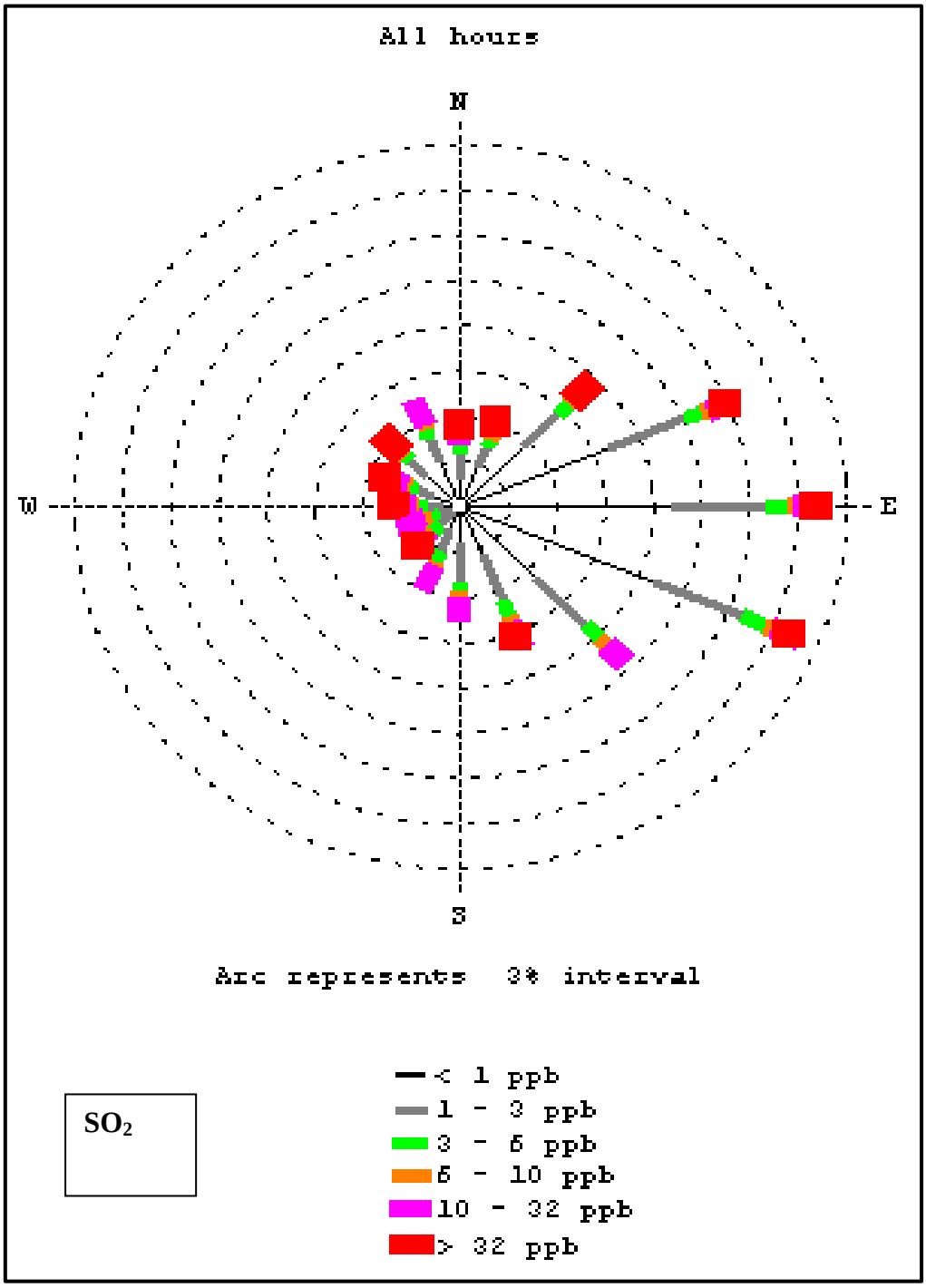

Figure 3. 25 SO_2 pollution rose recorded at Marapong monitoring station from 2007-2010

The highest sulphur dioxide values recorded are from the north eastern side and they align with the direction of the power station (Figure 3.25). The majority of the NO_x high values recorded at Marapong are from the south eastern part. They do not align with the direction of the power station. Both sulphur dioxide and nitrogen oxides emissions are emitted at low levels but there are some cases where the emissions are high. When the nitrogen oxide pollution rose diagram is compared with the sulphur dioxide pollution rose diagram it shows the same trends as the diurnal variation diagrams. The nitrogen oxide pollutants are higher in concentration than sulphur dioxide. Sulphur dioxide reaches a level of 32 ppb and nitrogen oxides reach up to 89 ppb (Figure 3.25 and 3.26).

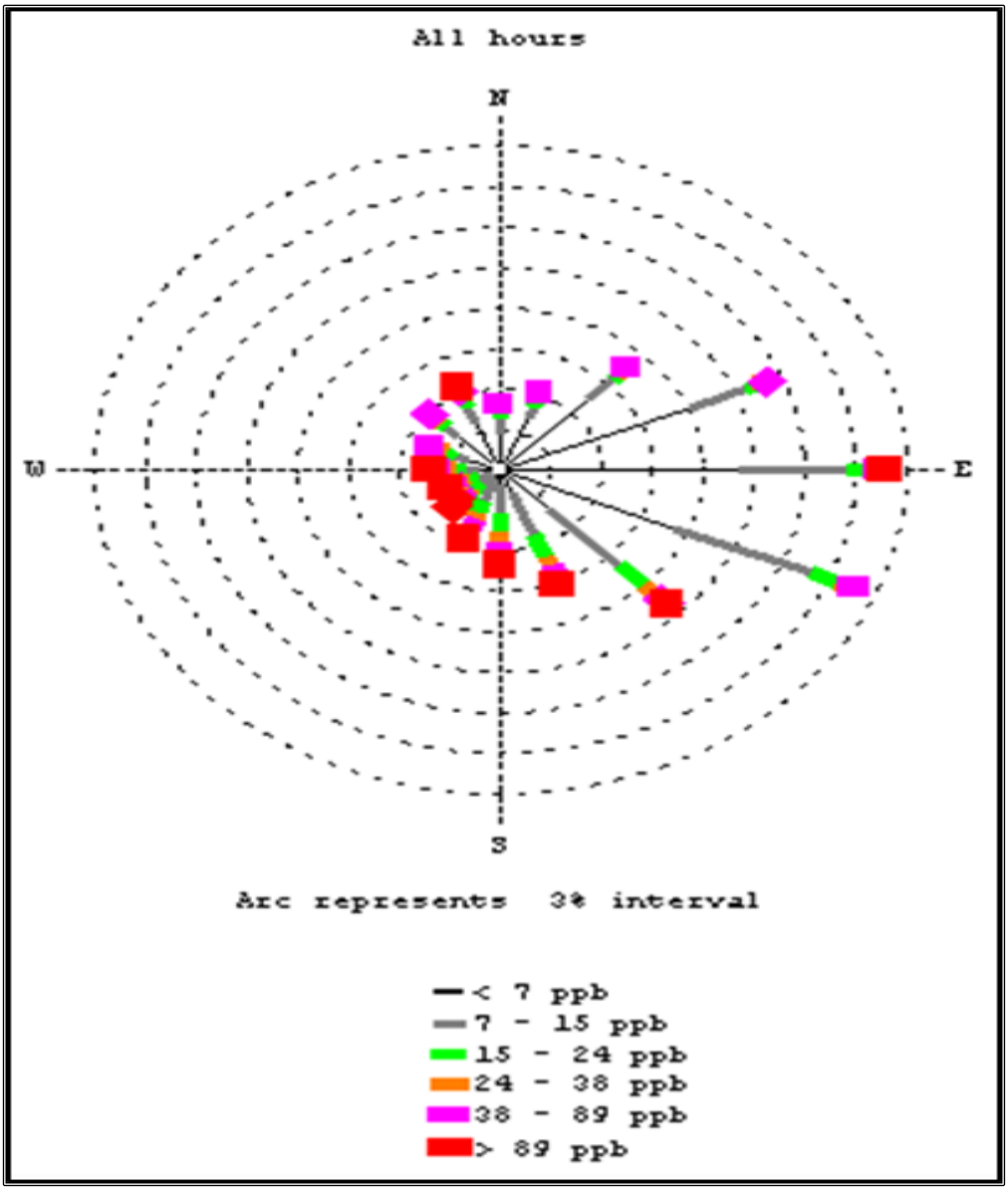

Figure 3. 26 NO_x pollution roses recorded at Marapong monitoring station from 2007-2010

In this chapter the ambient air quality monitoring data was analysed. The data used was from the period 2005-2010. The relationship between sulphur dioxide and nitrogen oxides was investigated. The influence of seasonality on the ambient air quality was studied. Chapter four will outline the modelling results.

Chapter 4: Modelling Results

This chapter outlines the simulated sulphur dioxide and nitrogen oxides concentrations in Lephalale. Nitrogen oxide was treated as nitrogen dioxide. The results were predicted by the AERMOD dispersion model. The averages used were hourly, daily and annual averages. They were presented in filled contours in order to display the spatial distribution of pollutants in Lephalale.

Simulated Sulphur dioxide concentrations

The hourly average concentrations predicted are above the national hourly standard. Most of the concentrations recorded were between 150 and 180 ppb. Higher concentrations were recorded at the south western side of the Matimba power station and on the north eastern side of the Matimba power station at Marapong Township (Figure 4.1).

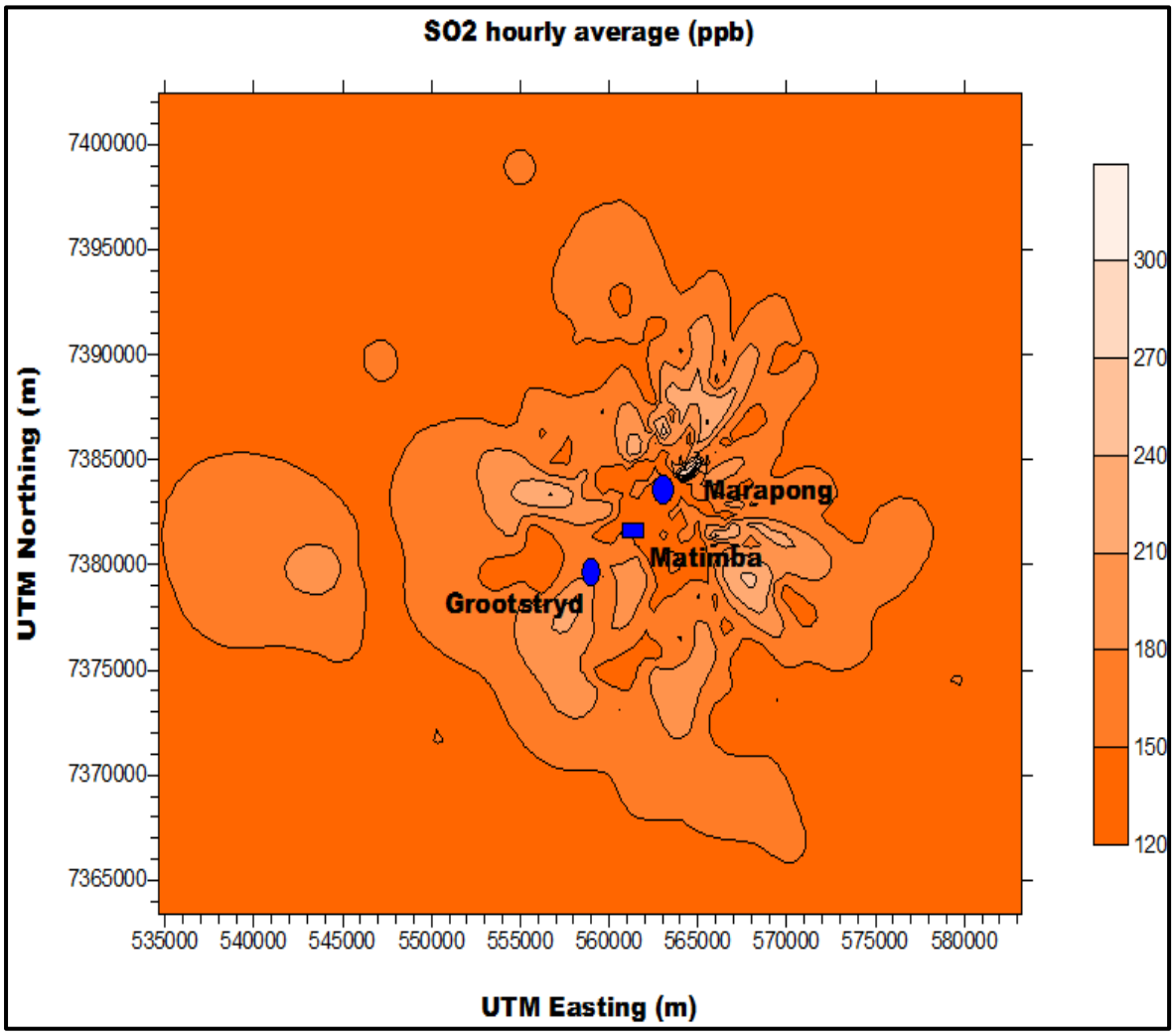

Figure 4. 1 Sulphur dioxide 1-hour average due to the power station for the year 2010 as simulated by AERMOD

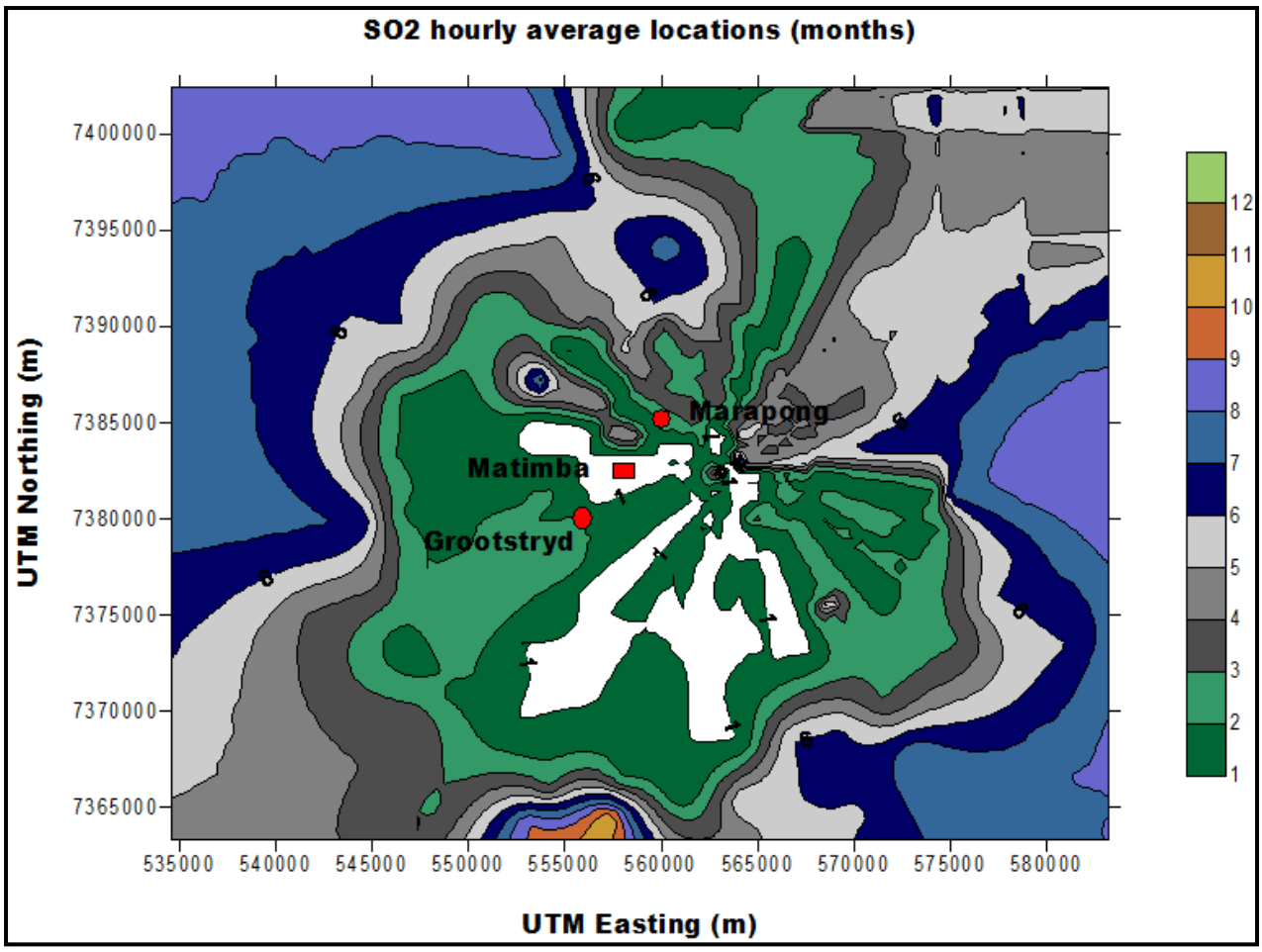

Figure 4. 2 Spatial distribution of SO_2 1-hour averages in terms of months for the year 2010 as simulated by AERMOD

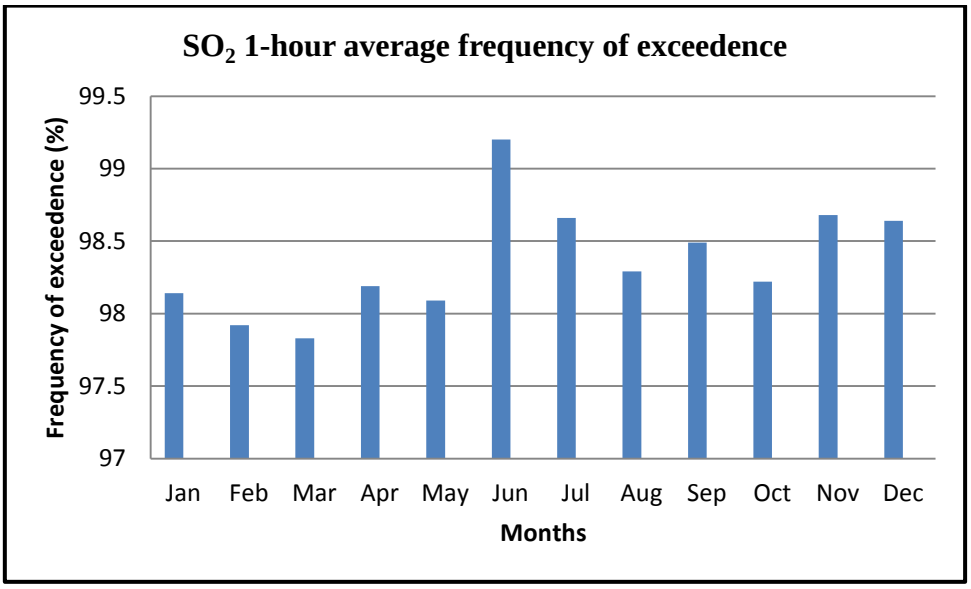

Figure 4. 3 SO_2 frequency of exceedence of the 1 hour average South African national ambient air quality standard (134 ppb)

Most of the concentrations predicted in close proximity to the power station occur during January and February (Figure 4.2). During these months the power station is expected to have a significant impact on the area. The frequency of exceedence of the hourly average is predicted to be above ninety percent for the whole year (Figure 4.3).

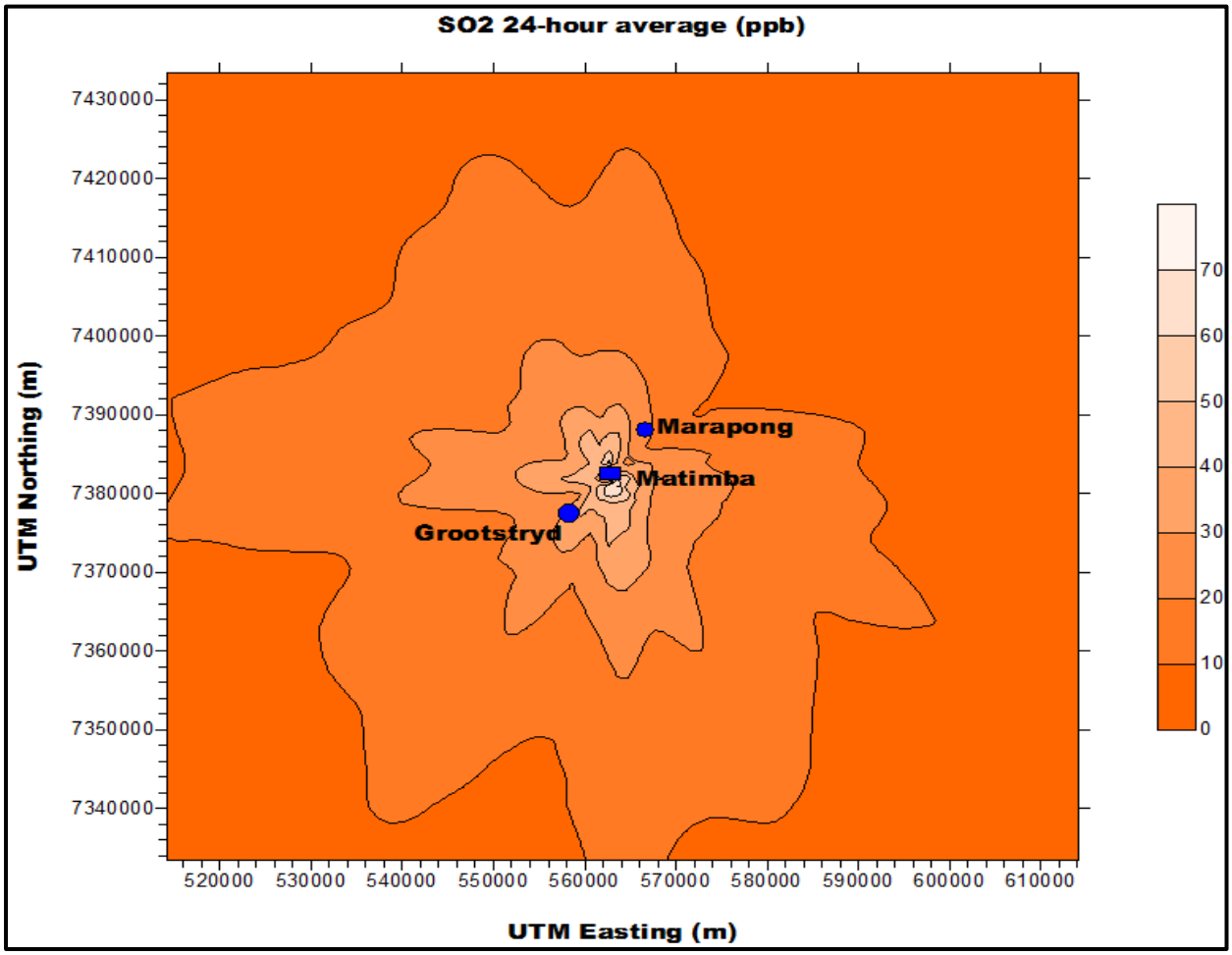

Figure 4. 4 Sulphur dioxide 24-hour average due to the power station for the year 2010 as simulated by AERMOD

Generally, the 24-hour average concentrations simulated by the model were below the national 24-hour standard (Figure 4.4). The frequency of exceedence recorded was below 43 percent. The highest percentages recorded in January and June. The highest values were recorded in close proximity to the power station. The simulation process showed that the majority of concentrations occurred during June.

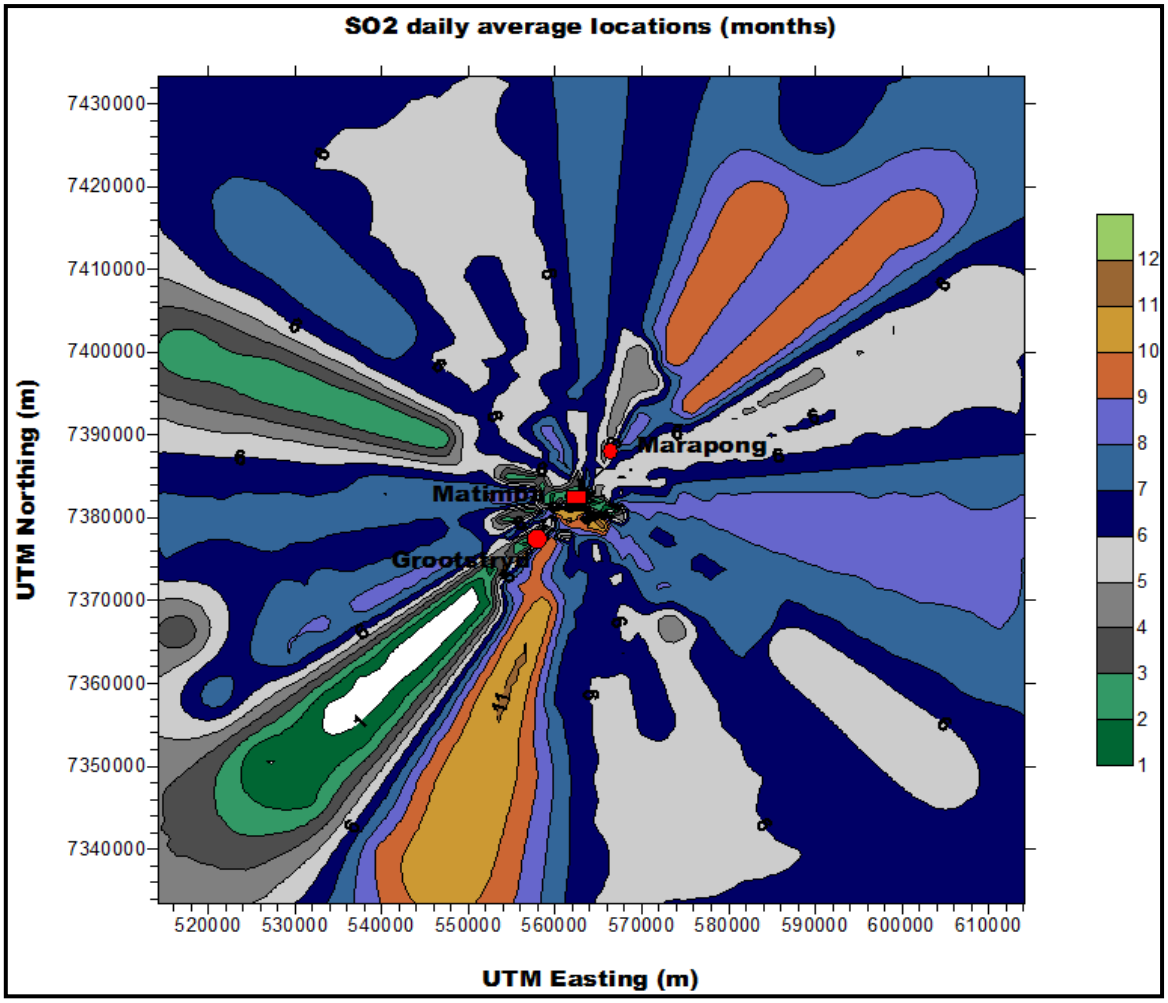

Figure 4. 5 Spatial distribution of SO_2 24-hour averages in terms of months for the year 2010 as simulated by AERMOD

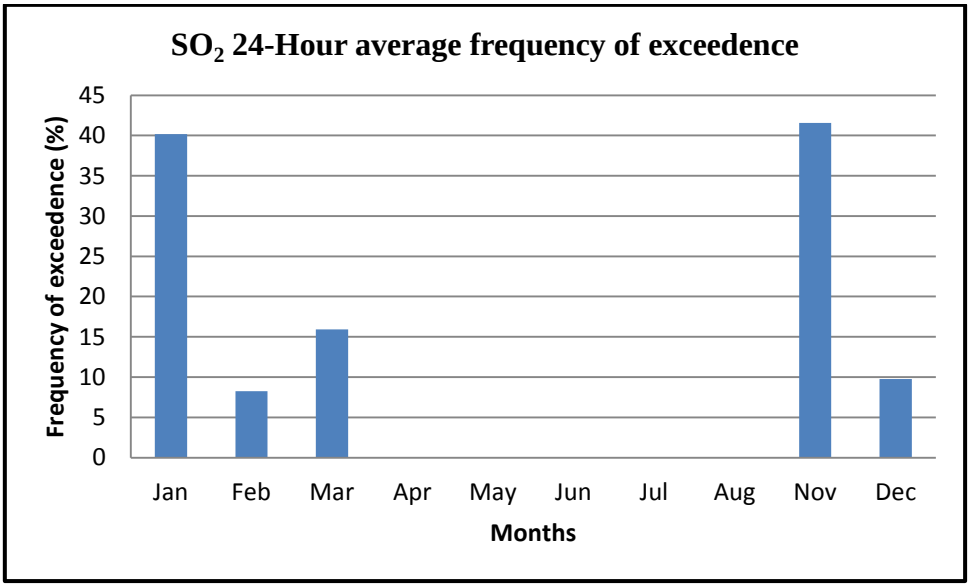

Figure 4. 6 SO_2 frequency of exceedence of the 24-hour average South African national ambient air quality standard (48 ppb)

The highest sulphur dioxide annual average concentrations were recorded in close proximity to the power station. The concentrations simulated decreased further from the power station. According to simulation, the pollutants plumes were moving in a southward direction from the power station. This is different from the general north-easterly wind direction where the expectation is that pollutants would move towards a south-westerly direction from the power station.

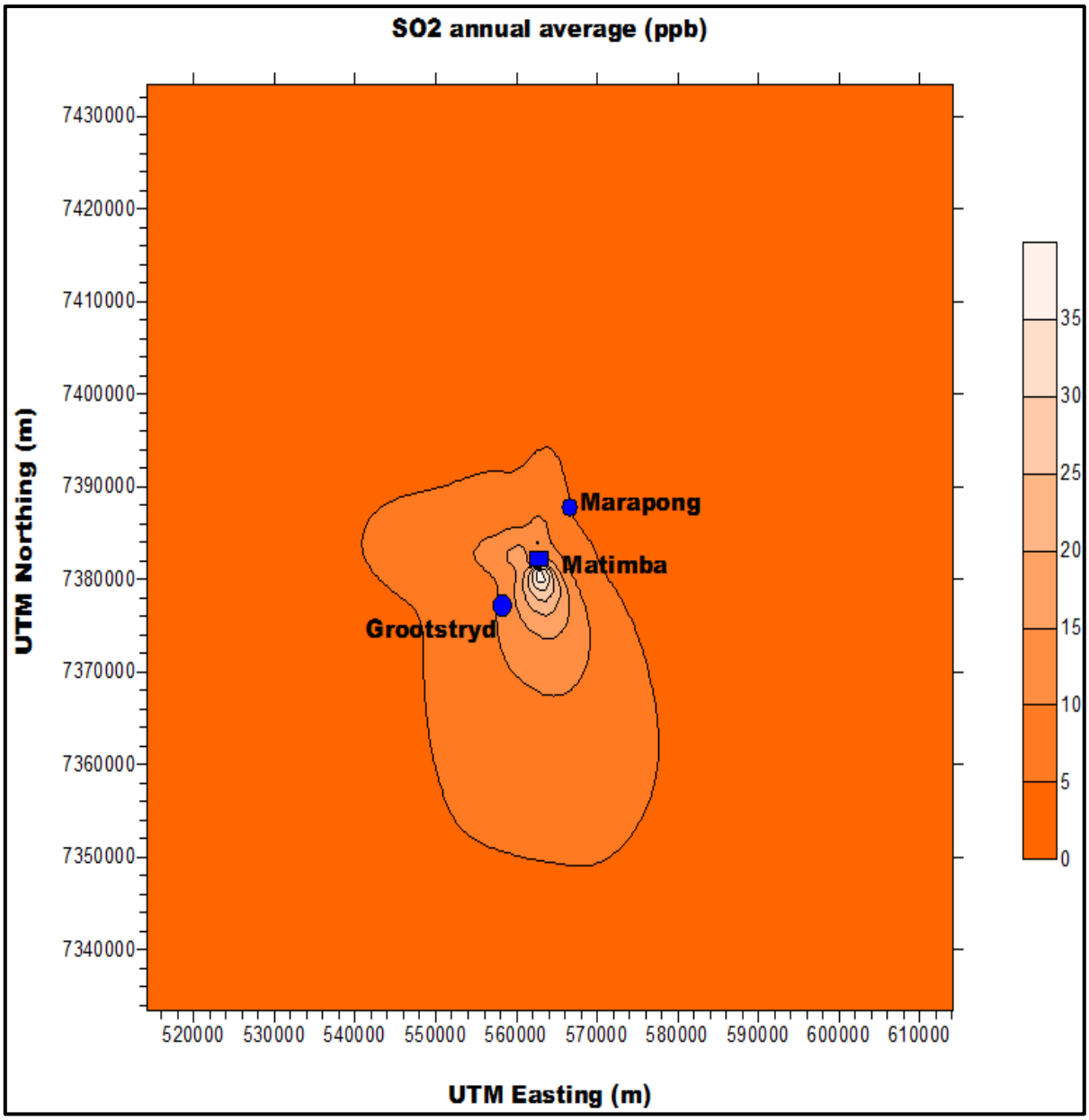

Figure 4. 7 Sulphur dioxide annual average due to the power station for the year 2010 as simulated by AERMOD

Simulated nitrogen dioxide concentrations

The simulated Nitrogen dioxide hourly averages show no specific trend. They are scattered over the modelled domain (Figure 4.8). During the majority of the months there were no exceedences recorded. The highest exceedence was recorded during June (Figure .4.9). Most concentrations recorded downwind of the power station are recorded during February and March. Within the overall modelling domain the concentrations were predominantly recorded during June (Figure 4.10)

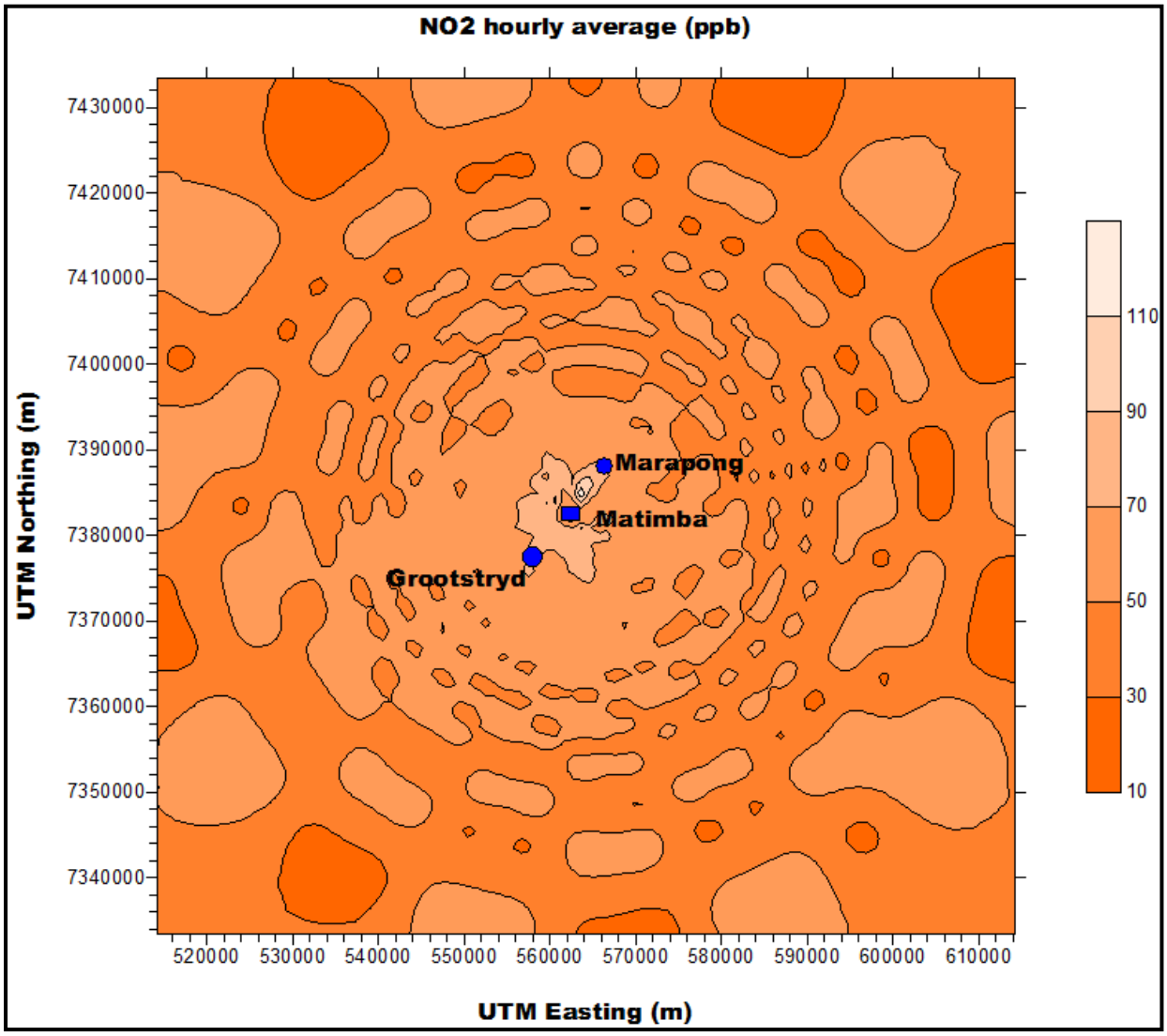

Figure 4. 8 Nitrogen dioxide 1-hour average due to the power station for the year 2010 as simulated by AERMOD

The highest daily average nitrogen dioxide concentration predicted by the model is 23 ppb. Higher concentrations are recorded in close proximity to the power station. The concentrations decrease with distance from the power station. The plumes predicted pursue

the dominant wind direction in the area. Most of the concentrations are simulated to occur during the months of June. Pollutants simulated to occur downwind of the power stations are predicted to occur during the months of January, February and March. It should be noted that there is currently no nitrogen dioxide 24-hour average standard in South Africa. However the nitrogen dioxide concentrations predicted by the model are low.

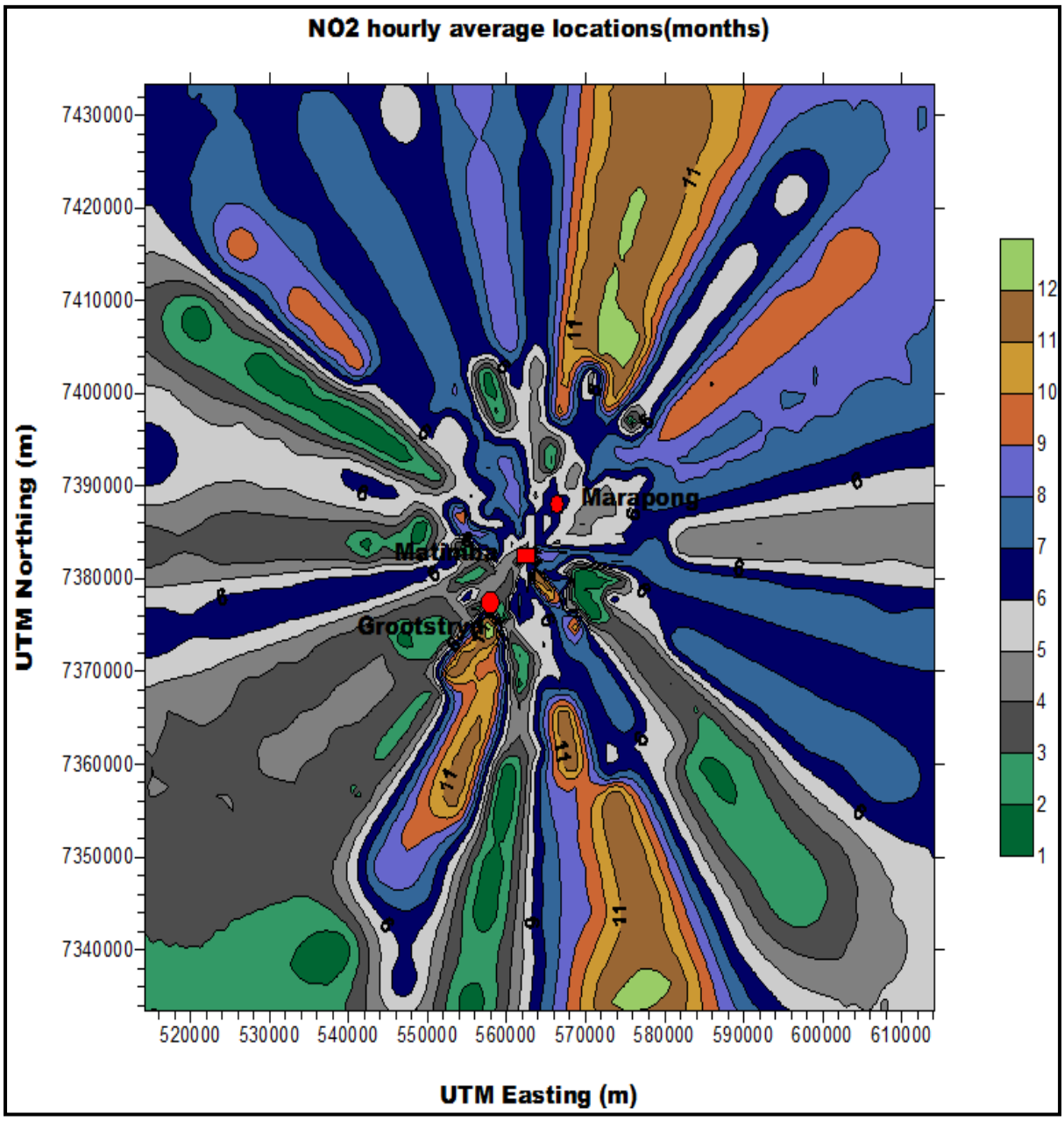

Figure 4. 9 Spatial distribution of NO_2 1-hour averages in terms of months for the year 2010 as simulated by AERMOD

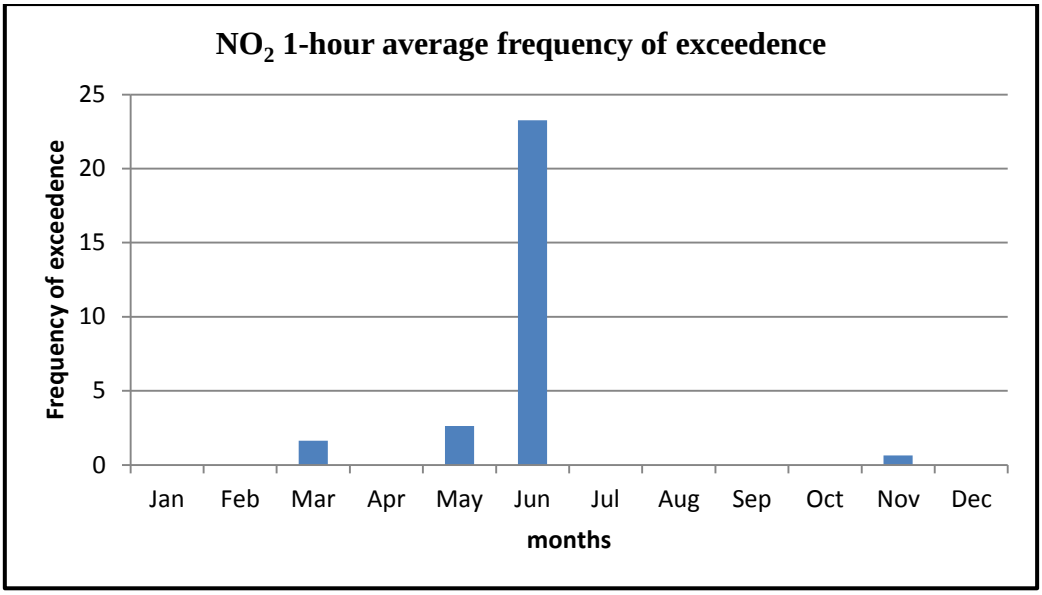

Figure 4. 10 NO_2 frequency of exceedence of the 1-hour average South African national ambient air quality standard (106 ppb)

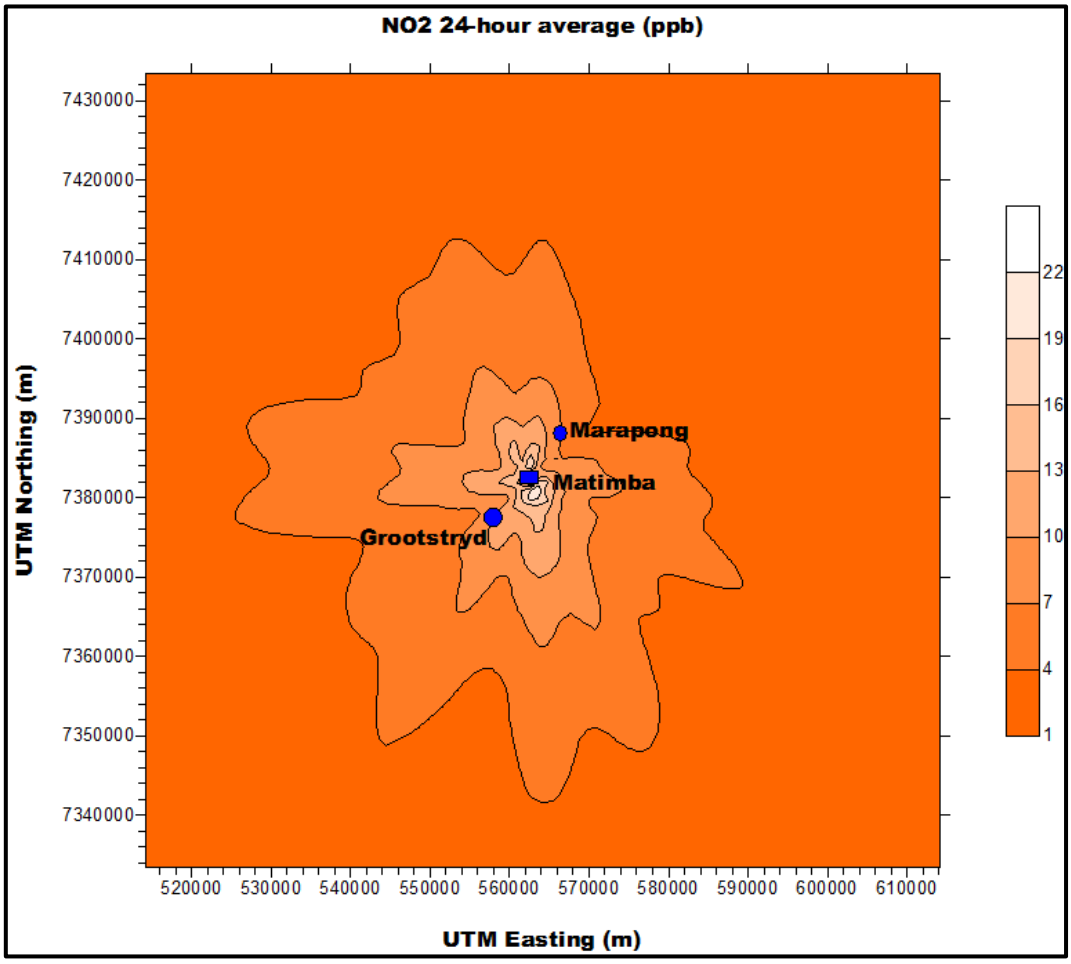

Figure 4. 11 Nitrogen dioxide 24-hour average due to the power station for the year 2010 as simulated by AERMOD

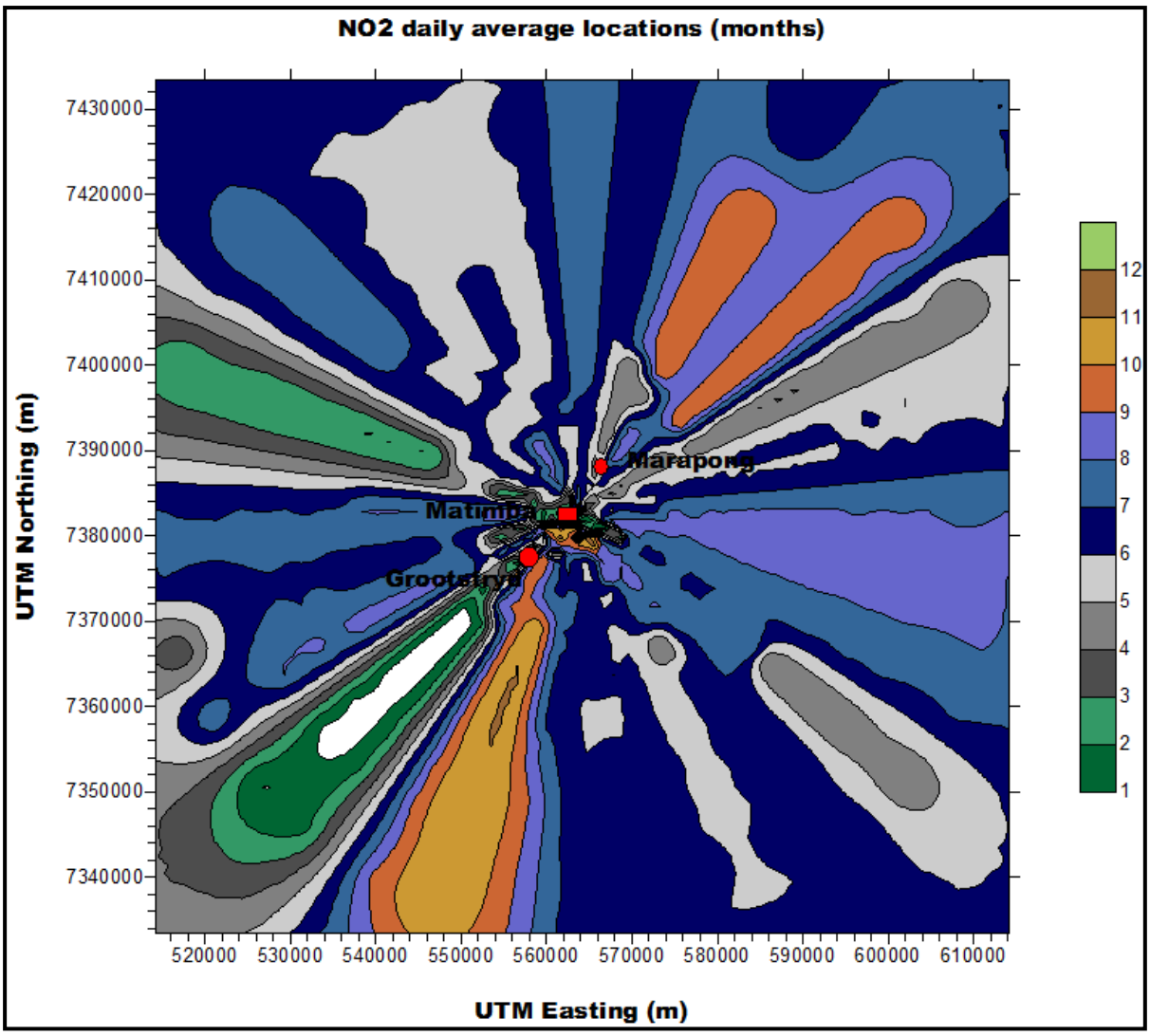

Figure 4. 12 Spatial distribution of NO_2 24-hour averages in terms of months for the year 2010 as simulated by AERMOD

The annual average of nitrogen dioxide concentrations that were simulated are below the South African ambient air quality annual standard of 21 ppb. The highest concentrations are predicted to occur in close proximity to the power station. The concentration plumes predicted are in a south-westerly direction from the power station. The pollutants from the power station are expected to mimic the direction of the dominant wind direction in the area. This plume strike shows that there are other sources of nitrogen dioxide besides the power station in the area.

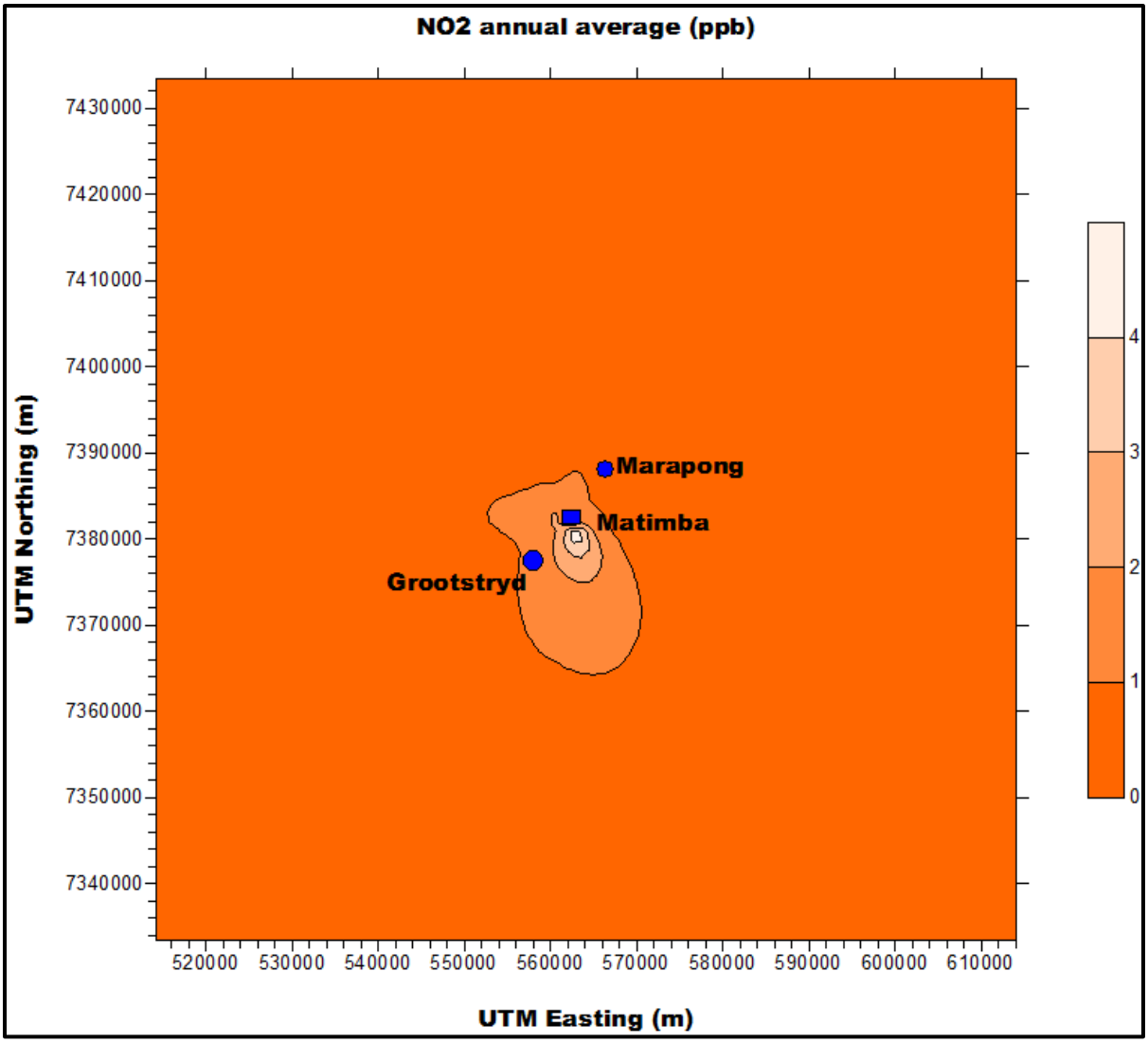

Figure 4. 13 Nitrogen dioxide annual average due to the power station for the year 2010 as simulated by AERMOD

Model verification

In order to assess the model performance the values simulated by AERMOD were compared to the monitoring data. It should be noted that AERMOD is a regulatory model. A regulatory model is not expected to give the exact same results as the monitored results. It is supposed to be conservative in nature. The regulatory model results are considered acceptable when they are within a factor of two (Rautenbach *et al*, 2009).

The highest measured average values were compared against the highest simulated values at both Marapong and Grootstryd monitoring stations (Table 4.1). All the values for sulphur dioxide were acceptable as they were within a factor of two. The model over-predicted the one-hour highest value for Marapong and under -predicted the one for Grootstryd.

For the highest 24-hour average the model over-predicted values for both Marapong and Grootstryd monitoring stations (Table 4.1). All the 24-hour highest values were acceptable as they were within a factor of two. The results were considered acceptable when the sulphur dioxide ratio between the highest measured values was compared to the highest simulated values.

The highest measured nitrogen dioxide averages were compared with the simulated averages. It was then established that the model had over-predicted the one-hour averages and under-predicted the 24-hour average. Nitrogen dioxide was not measured in Grootstryd when the monitoring station was still operational.

Table 4. 1 Comparison of the highest recorded value from the monitoring stations and the highest simulated value by AERMOD model

	Highest 1 hour value		**Highest 24 hour value**		**1 hour simulated/ measured**	**24 hour simulated/ measured**
sulphur dioxide(ppb)						
	measured	simulated	measured	simulated		
Marapong	117.47	139	23.60	37.12	1.18	1.57
Grootstryd	206.00	202	43.47	45.64	0.98	1.04
Modelled area	498.54		73.25			
nitrogen dioxide (ppb)						
Marapong	84.20	210	29.82	11.30	2.49	0.37
Grootstryd	-	-	-	-	-	-
Modelled area	151.84		22.31			

The highest measured and simulated sulphur dioxide values were compared against the South African national standard. All the values both measured and simulated at Marapong monitoring station were below the national standard except for the simulated one-hour average (Table 4.1). The sulphur dioxide one-hour values at Grootstryd were above the national ambient air quality standards and both the simulated and measured values were below the 24 hour national ambient air quality standard.

The nitrogen dioxide values for Marapong monitoring station were compared against the South African national ambient air quality standards. It was established that the measured

one-hour average value was below the national standard whereas the simulated one was above the national standard.

It should be noted that all the values -measured and simulated - at Marapong are lower than the values at Grootstryd. The high values that occur at Grootstryd can be ascribed to the dominant wind direction in the area and the location of the power station. Marapong is located upwind of the power station whereas Grootstryd is located downwind of the power Station. The location of the Grootstryd downwind of the power station was an advantage because it could record a maximum concentration of pollutants emitted from the power station.

Chapter four discussed the outputs simulated by AERMOD. The averaging periods used were 1 hour, daily and annual periods. The model was verified by comparing the maximum concentrations to the monitoring data. The research conclusions will be discussed in chapter 5

Chapter 5: Conclusions

This chapter concludes the main findings of this study on the ambient air quality impact of the Matimba power station within Lephalale. The study is based on the analysis of monitoring data and the modelled results simulated by AERMOD.

The primary aim of this study was to determine the impact of the Matimba power station on the ambient air quality in Lephalale area. This was achieved by the use of monitoring data from the period 2005-2010. The monitoring data was obtained from the Grootstryd (2005-2006) and Marapong (2007-2010) monitoring stations. The criteria pollutants that were analysed were sulphur dioxide and nitrogen oxide.

The location of Grootstryd downwind of the Matimba power station was highly significant as it created the potential for recording the maximum influence of the power station on the ambient air quality of the area. For the hourly averaging period a total of 15 exceedences were recorded between 2005 and 2006, which is lower than the current ambient air quality limit of 88 exceedences per annum. However no exceedences were recorded during the 24 hour average period. It was noted that the sulphur dioxide emissions are high but the power station is in compliance to the 24 hour and the annual limit of exceedence.

The diurnal variations from the Grootstryd monitoring station indicated a typical tall-stack diurnal signature. The pollution roses also confirmed that most of the pollutants were from the power station. From the peak shown by the seasonal diurnal variation and the pollution roses it was confirmed that most pollutants are from the north eastern sector which is in alignment with the power station. It should however be noted that there are also other low-level sources which were not identified.

At Marapong monitoring station sulphur dioxide and nitrogen oxides were monitored. Only 8 exceedences were recorded for the sulphur dioxide hourly average, which indicates that the power station is in compliance with the national hourly standards. No exceedences were recorded for the 24-hour average. The sulphur dioxide diurnal variation diagram indicated a typical tall-stack signature. Even though the diurnal variation signature was that of the power station, the pollutants recorded were very low and they were under the 24-hour ambient air quality standard. The seasonal variations diagrams indicated that most of the recorded peaks were from the low-level sources and the power station did not have an influence on these

peaks. Very few peaks that aligned with the direction of the power station were recorded during the winter months. The pollution roses also confirmed that the power station is not the only source of the sulphur dioxide emissions in the area. When the values recorded at Marapong are compared with the ones from Grootstryd it is clear that higher values are recorded at Grootstryd. This can be attributed to the positioning of the Monitoring station in relation to the power station and the dominant wind direction in the Lephalale area.

The nitrogen oxides hourly and daily average concentration recorded at Marapong were significantly higher than those of sulphur dioxide. The diurnal signature for nitrogen oxide showed a bimodal signature which is a typical low-level source signature. Form the pollution roses and the seasonal diurnal variations it can be deduced that the power station has no significant influence on the emissions of nitrogen oxide. Most of the nitrogen oxides might be from the domestic activities and motor vehicles seeing that the monitoring station is located upwind of the power station within the Marapong Township.

The relationship between nitrous oxide and nitrogen dioxide was further studied. From the scatter plot it was established that there is, to a certain degree, a positive relationship between nitrous oxide and nitrogen dioxide. From the diurnal variation it was ascertained that nitrogen oxide is higher in the morning and it becomes lower in the evening when compared to nitrogen dioxide. The increase in nitrogen dioxide in the evening is associated with photochemical reactions. During the winter season nitric oxide is higher than nitrogen dioxide most of the hours of the day and even in the evening. This can be ascribed to a low level of sunlight which then excludes photochemical reactions.

From the scatter plots it was identified that sulphur dioxide and nitrogen oxides have a negative relationship. The negative relationship indicates that they are not from the same sources. Nitrogen oxides' diurnal variations signature indicates that the major sources are ground-level sources. The sulphur dioxide diurnal variation indicates that the power station and ground level sources contribute to higher levels which are, however, still below the national standards. Seasonality has an impact on the level of pollutants recorded at Lephalale. Higher values are recorded during the winter season when the conditions are calm and there are no high turbulences. High turbulences cause mixing and dilution of pollutants.

Simulation showed that higher sulphur dioxide values occurred downwind of the power station. Higher sulphur dioxide concentrations were simulated to occur in close proximity to the power station and decreased with distance from the power station. The modelling results

indicated that the power station has a significant impact on the ambient air quality within Lephalale. Higher sulphur dioxide values were simulated to occur at Grootstryd than Marapong monitoring station. The simulated results followed the same trend as the monitoring results

The sulphur dioxide results were more realistic as they increased in distance from the power station. The 1-hour average was predicted to have a higher exceedence of the ambient air quality standard. Higher concentrations were simulated to occur during January and February. This is in line with the results given by the monitoring station. These results indicate that seasonality has an influence on the level of concentrations in Lephalale. As expected the sulphur dioxide concentrations were simulated to occur in summer.

Nitrogen oxide values were simulated to be lower than the sulphur dioxide concentrations. It should be noted that the nitrogen oxide values were modelled as nitrogen dioxide. The model predicted the highest frequency of exceedence to occur during June and July. This simulation is in agreement with the monitoring results. This higher frequency of exceedence is ascribed to low sunlight during winter season which allows for higher nitrogen dioxide formation.

The model under-predicted annual nitrogen dioxide concentrations. The simulated 1-hour average and the simulated monthly spatial distribution of pollutants indicate that the nitrogen dioxide pollutants are scattered all over the area. This indicates that the power station is not the only source of nitrogen dioxide in the area. These results are supported by the diurnal variations of the monitoring data.

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