MODELLING SO_2 EMISSIONS FROM ANGLOGOLD ASHANTI'S EAST ACID PLANT: DETERMINING IMPACTS ON AMBIENT AIR QUALITY

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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 in any other University.

_____

(Malusi Buthelezi)

_____day of_____2009

In memory of my Father

Wellington Dubuza Buthelezi

(1948 – 1997)

ABSTRACT

Since the promulgation of the new air quality legislation in South Africa, sulphur dioxide (SO_2) has been a pollutant of concern especially in the heavily industrial South African regions. AngloGold Ashanti's sulphuric acid (H_2SO_4) plant located in Klerksdorp, North West province is an important local source of SO_2. Other important sources in the North West province include the platinum mine smelters which are responsible for elevated SO_2 concentrations in the Rustenburg area. The impacts of these emissions are exacerbated by the poor atmospheric dispersion potential for a substantial portion of the year. An air dispersion modelling study undertaken by Scorgie and Venter (2004a) indicated that the AngloGold Ashanti's East Acid Plant was likely not to comply with its Air Pollution Prevention Act (APPA) registration certificate (RC) conditions and the proposed South African ambient air quality standards. AngloGold Ashanti subsequently implemented emission reduction measures to minimise elevated SO_2 levels and for the first time initiated continuous emission monitoring in the stack and the nearby village. This study aimed at determining the impacts from implementing emission control measures in 2007 whilst establishing the relationship between quantified stack emissions, modelled and monitored ambient air quality data. Other AngloGold Ashanti SO_2 sources i.e. South Uranium Plant and Great Noligwa No. 8 Gold Plant were included in the model runs to assess their contribution to the cumulative SO_2 concentrations. AERMOD was applied to examine the dispersion potential of stack and fugitive emissions. Modelled SO_2 stack concentrations were within the current South African ambient air quality standards for all averaging periods prior and post East Acid Plant shutdown[1]. However, exceedances were noted for 1-hour and 24-hour averaging periods for modelled stack and volume sources combined i.e. East Acid Plant, South Uranium Plant and Great Noligwa No. 8 Gold Plant. The stack emissions and ambient data compared well with an exception of the fugitive emissions. The model demonstrated a satisfactory performance to calculate stack emissions from the East Acid Plant. However, the model compared poorly with the monitored ambient air quality data partly due to the lack of comprehensive emission factors for fugitive sources. Based on these results it can be concluded that the Acid Plant stack concentrations solely, do not pose significant health risk to the nearby receptors and that the implemented air pollution abatement measures are mostly effective. However, it is important to note that the model may have underestimated fugitive emissions which contribute to low-lying emissions thus impacting on sensitive receptors.

[1] Shutdown refers to a Plant shutdown for scheduled major maintenance work that last about a month

PREFACE

Global anthropogenic emissions of various pollutants began to increase with the industrialisation and anthropogenic fuel use, and have continued to increase in 21st century. High emission density of the primary pollutants particularly sulphur dioxide (SO_2) is evident and SO_2 emissions have increased by a factor of three on a global scale fuelled by industrialisation amongst other factors (Annegarn et al., 1996; Pham et al., 1996; Zunckel et al., 2000; Smith et al., 2001). As a criteria pollutant, sulphur dioxide is a pollutant of concern due to the significant environmental impacts e.g. wet/dry deposition and health impacts associated with its release or exposure under extensive and persistent inversions and stable layers (Barenbrug, 2003). Given the multi-dimensional impacts of emissions of sulphur dioxide, it is therefore important to have an accurate estimate of the magnitude and pattern of emissions particularly from significant local sources (Smith et al., 2001). An air dispersion model is a common scientific tool applied to estimate such an extent and pattern of concentrations.

In this research report, sulphur dioxide emissions from AngloGold Ashanti's East Acid Plant and other nearby sources in Vaal Reef are discussed. An air dispersion modelling exercise was undertaken to evaluate the impacts of AngloGold Ashanti's specific activities on sulphur dioxide levels in the area. The level of compliance with the South African sulphur dioxide guidelines and standards was also assessed. In addition, the impact of installing air pollution management measures was determined. This research report is divided into four chapters: **Chapter 1** introduces regional air quality and discusses the pollutants and meteorological conditions influencing air quality. Important sources of sulphur dioxide emissions and those specific to AngloGold Ashanti Vaal River operations are highlighted and the previous modelling study. Stack emissions and monitored ambient air quality data is presented and research goals are outlined. **Chapter 2** highlights air quality and monitoring at Vaal River operations. The model (AERMOD) and input data are described. The meteorological conditions in the study area are discussed. **Chapter 3** provides a discussion of the modelling results. **Chapter 4** introduces a summary of the findings of this research and provides conclusions to them.

Part of this research report was presented in a local air quality conference i.e. National Association for Clean Air (NACA), held in Drakensburg (KwaZulu-Natal) from 10-12 October 2007. I would like to thank AngloGold Ashanti Limited for partly financing second year of my study. Thanks to Roelof Burger for his valuable assistance in many respects particularly with data formatting and changes to the planetary boundary layers statistics. Thanks to Jovic Vladimir of Gondwana Environmental Solutions for assistance with Franson CoordTrans and TatukGIS. Gareth Davis and the whole support team at Lakes Environmental in Canada are thanked for their support with AERMOD (AERMAP). Extended thank you to the ex-colleagues at the East Acid Plant i.e. Jan Jacobs, John Grewar, Charles Wade, Zandile Mhlungu for their assistance and mass balance data. A note of appreciation to the AngloGold Ashanti's Vaal River Environmental Management and Survey Departments for endless support especially Charl Human and Knut Norman. The Buthelezi family and dear friends are greatly thanked for all the moral support they provided during this study and my career at large. A note of appreciation to the Climatology Research Group for kind support during study. This research was done under the guidance of Prof Stuart Piketh (Supervisor) and Dr Kristy Ross (Co-supervisor), who are thanked for their continuous supervision and guidance during this research project.

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Nomenclature

ADMS	Advanced Dispersion Modelling System
AERMOD	AMS/EPA Regulatory Model Improvement Committee Model
AGA	AngloGold Ashanti
APPA	Air Pollution Prevention Act
AQA	Air Quality Act
CAPCO	Chief Air Pollution Control Officer
CALPUFF	Californian Puff Model
CEM	Continuous Emission Monitoring
DEAT	Department of Environmental Affairs and Tourism
EAP	East Acid Plant
EC	European Commission
EF	Emission Factor
H_2SO_4	Sulphuric Acid
ISC	Industrial Source Complex
ISCS3	Industrial Source Complex Short-Term 3
MM5	Mesoscale Model 5
PBL	Planetary Boundary Layer
RC	Registration Certificate
S.A	South Africa
SO_2	Sulphur Dioxide
SO_4^{2-}	Sulphate
TAPM	The Air Dispersion Model
USEPA	United States Environmental Protection Agency
UTM	Universal Transverse Mercator
VR	Vaal River

CHAPTER 1 : OVERVIEW

Chapter one gives an overview of AngloGold Ashanti's East Acid Plant as an important source of SO_2 emissions. Other industries and/or sources (within AGA) contributing to SO_2 emissions in the area are highlighted. Air pollution in a local context especially the Highveld region (North West Province) is discussed. Dispersion potential of pollutants in the study area will be cited and outline of research goals given. Previous modelling study, stack emissions, monitored ambient air quality data is presented

1.1. Introduction

Air quality has over the years deteriorated at a local and international scale. This is most evident in the heavily industrialised regions e.g. the Highveld which are characterised by the high population densities and rapidly growing economies (Siniarovinaa and Engardtb, 2005). Industrialisation, amongst other factors, has largely resulted in the high emission density of the primary pollutants particularly sulphur dioxide (SO_2), and critically the SO_2 emissions have increased by a factor of three on a global scale (Annegarn et al., 1996; Pham et al., 1996; Zunckel et al., 2000; Smith et al., 2001). SO_2 is widely known as a predominant anthropogenic sulphur-containing air pollutant emitted from natural sources, industrial activities and combustion processes (Baumbach, 1996; Pham et al., 1996; Seinfeld and Pandis, 1998). This gas is one of the six criteria pollutants (or pollutant of concern) due to the significant environmental impacts e.g. wet/dry deposition and health impacts associated with its release or exposure under poor atmospheric conditions.

In line with international best practice, South Africa is adopting stringent emissions limits and ambient air quality standards to minimise human health risks and negative environmental impacts. This conforms to the approach of the 'new' National Environmental Management: Air Quality Act, 2004 which focuses on the receiving environment i.e. ambient air quality and sets stricter limits and standards. Given the multi-dimensional impacts of SO_2 emissions, it is therefore important to have an accurate estimate of the magnitude and pattern of such emissions (Smith et al., 2001).

AngloGold Ashanti's (AGA) East Acid Plant located in Vaal Reef (Figure 1.1), Klerksdorp facilitate gold extraction from pyrite and produces sulphuric acid (H_2SO_4) which results in the release of SO_2 to the atmosphere. AGA's dormant West Acid Plant is located in Orkney about 15 km from Vaal Reef. This plant was decommissioned in 2005 due to the lack of pyrite and non-compliance with SO_2 emission limits set by the then Chief Air Pollution Control Officer (CAPCO).

AGA also operates a South Uranium Plant using coal fired boilers which negligibly contributes to the cumulative SO_2 emissions in the ambient air. AGA is an important source of economy and SO_2 emissions in this region together with some of the large industries and platinum mine smelters in the Rustenburg area. A medical waste incinerator located in Vaal Reef about 10 km north west of the East Acid Plant further contributes to gaseous pollutants in the area (Figure 2.2).

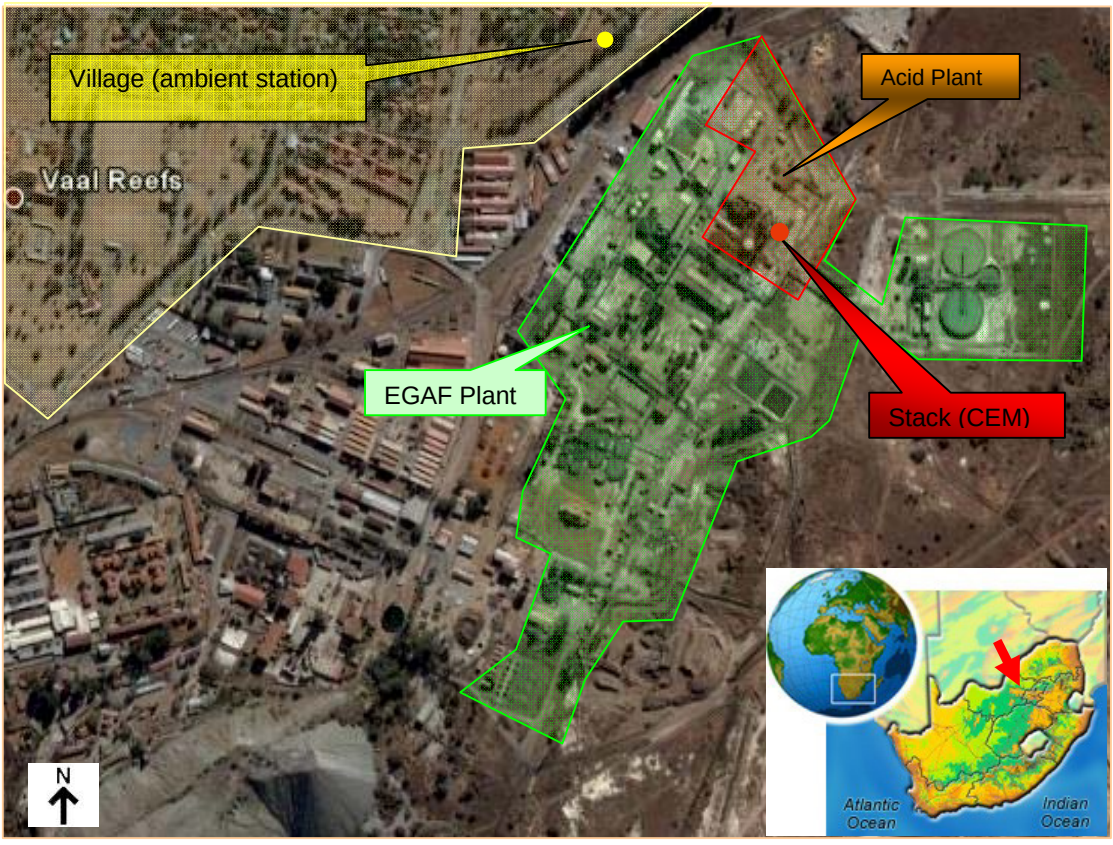

Figure 1.1: Location of AngloGold Ashanti's East Acid Plant stack (red) and ambient monitoring station (yellow) (after earth.google.com, 2007)

A dispersion modelling study undertaken by Scorgie and Venter (2004a) indicated that the AngloGold Ashanti East Acid Plant was likely not to comply with its Atmospheric Pollution Prevention Act (APPA) registration certificate (RC) conditions and the proposed ambient air quality standards. Air pollution control measures such as re-engineering weak acid stripper to improve its SO_2 removal efficiency from calcine water have been implemented to reduce the emissions. This research project aimed at establishing the extent of positive impacts these emission control measures have on the ambient air quality. AERMOD, a steady-state Gaussian plume atmospheric dispersion model was applied to achieve this objective. AERMOD's suitability to predict the Acid Plant's emissions was also assessed. The dispersion modelling results were validated against the observed SO_2 concentrations at the nearby ambient air quality monitoring station.

1.2. AngloGold Ashanti's sulphuric acid (H_2SO_4) process

The contact sulphuric acid production process particularly in the aging and often inefficiently maintained plants results in SO_2 fugitive emissions leaking from the hot heat exchanger, the roasters and other sensitive areas of the plant. Such fugitive emissions must be controlled due to the poor dispersion potential of climatology in the North West province exacerbated by the extensive and persistent inversions and stable layers (Garstang et al., 1996). Turner (1996:72) points out that 'pollutants emitted at low-level during the night are poorly dispersed in the stable boundary layer (SBL) and this results in higher concentrations being experienced at ground level in the vicinity at source'. However during the day the concentrations tend to be low due to large surface turbulent fluxes and many dispersion models can give satisfactory predictions for both scenarios given reasonably good input data (Turner, 1996; Baumbach, 1996).

AngloGold Ashanti's (AGA's) East Acid Plant was commissioned in the late 1960's (after the promulgation of the APPA) in order to facilitate gold extraction from pyrite and produce sulphuric acid (H_2SO_4) for the uranium leach process. A maximum of 250

tons of 100% sulphuric acid per day is produced and a targeted daily production is 223 tons. The process chemistry entails the following reaction, Eqs. (1)– (4):

$4FeS_2 + 11O_2 \longrightarrow 2Fe_2O_3 + 8\ SO_2$ (Roasting – Excess Oxygen) Hematite (1)

$3FeS_2 + 8O_2 \longrightarrow Fe3O_4 + 6SO_2$ (Roasting) Magnetite (2)

$2SO_2 + O_2 \longrightarrow 2SO_3$ (Conversion) (3)

$SO_3 + H_2O \longrightarrow H_2SO_4$ (Absorption) (4)

(Inorganic Chemical Industry, 1995; Seinfeld and Pandis, 1998; Jacobs, J, personal communication; 05 October 2007)

In the roaster process, the pyrite is repulped to a relative density of approximately 2.0 before being fed to the roaster feed guns of two parallel fluidised bed roasters. Pyrite combustion results in an operating temperature of 750^{o}C to 800^{o}C and this temperature is maintained by the exothermic reaction resulting from the burning of fresh pyrite. Following the roasting stage the two products i.e. gas and calcine are treated separately. The gas is purified and cooled in the cyclones, Swemco Tower, Electrostatic Mist Precipitators and Stripping Tower. The purified and cooled gas at approximately 7-8% SO_2 is dried in the drying tower using 93% sulphuric acid. With the aid of a blower the gas is delivered via heat exchangers to a four-stage converter. In the converter use is made of a Cesium based catalyst to convert the sulphur dioxide to sulphur trioxide. The trioxide gas is absorbed using 98% sulphuric acid and the resultant acid is diluted with the acid emanating from the drying tower to produce a net increase in 98% sulphuric acid stock. The waste gases are dispersed into atmosphere via the 53 metre stack (Figure 1.2) (de Nevers, 1995; EMPR, June 2001 as cited in Scorgie and Venter, 2004a; Smith, 2002).

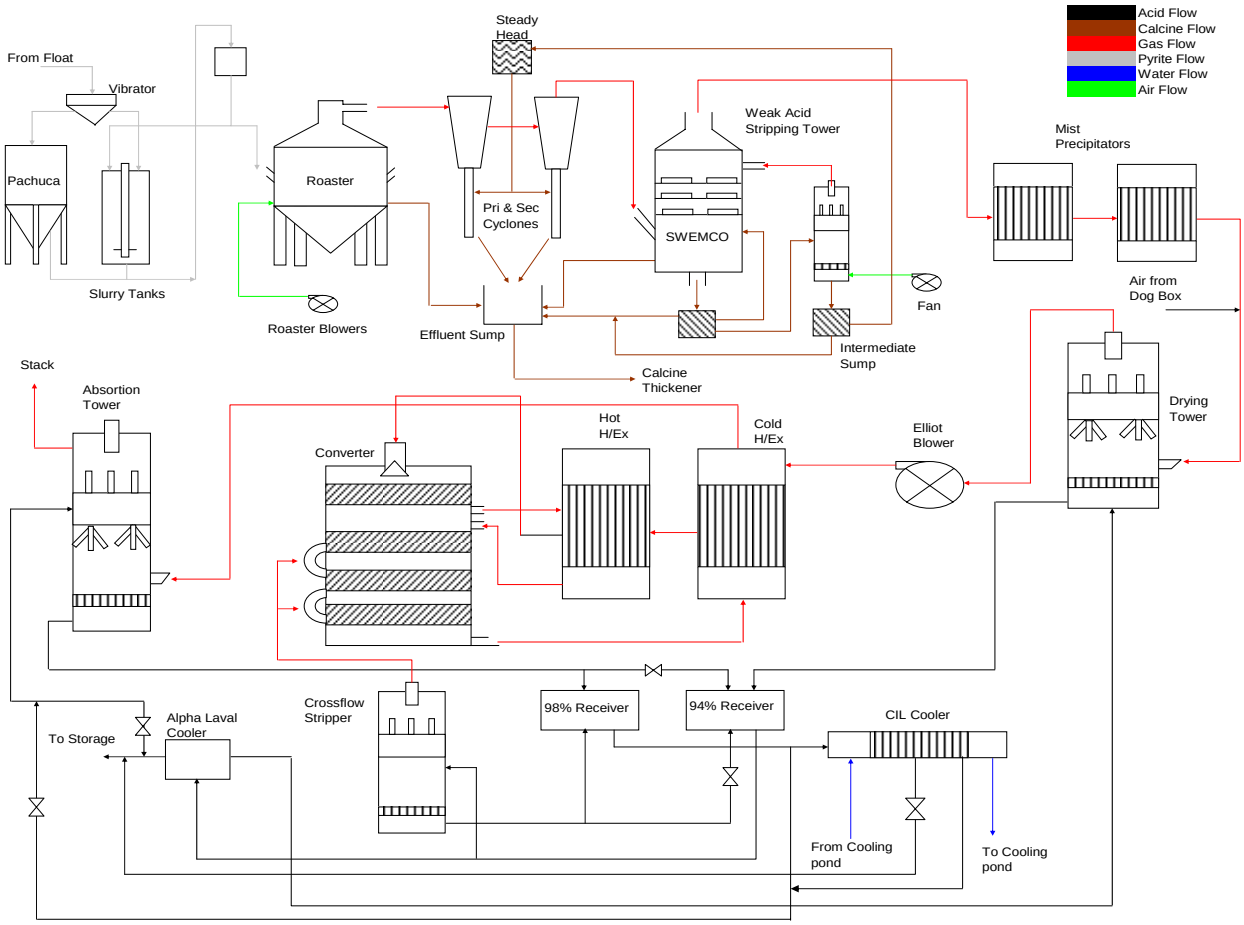

Figure 1.2: AngloGold Ashanti's East Acid Plant Process Flow Diagram (PFD)

1.3. Sulphur dioxide emissions from the East Acid Plant and the North West Province

A major pollutant resultant from the initial oxidation of sulphur in the feedstock (pyrite) is SO_2 and it is important to control the release of this pollutant into the ambient air to minimise associated negative environmental and health impacts. Some of the widely applied SO_2 control systems include limestone or lime injection (dry/wet), sodium carbonate inoculation, citrate process, copper oxide adsorption and caustic scrubbing (Boubel et al., 1994). Since the promulgation of air quality legislation, SO_2 has been identified as a pollutant of concern particularly in the heavily industrialised Highveld region. Industrial activities entailing largely metallurgical processes in the North West

province are important sources of sulphur dioxide with some activities contributing to significant levels of ambient SO_2 concentrations (Potgieter and Bryszewski, 2005). The power generating plants also contribute to SO_2 emissions because of the large amount of (low grade) coal used (Held et al., 1996a; Zhou et al., 2003). However due to the expansion and increasing diversity in industries and the resultant cumulative emissions of SO_2 (and other pollutants), it has become necessary to closely monitor these industries to ensure that levels of process emissions are regulated and maintained within permissible limits/standards. Moreover, the ground level concentration of SO_2 emissions from the domestic coal burning and traffic contributes to pollution episodes especially in the Highveld region.

Sulphuric acid (H_2SO_4) is one of the major inorganic chemicals in modern industry and production processes associated with H_2SO_4 are controlled and/or monitored due to the resultant toxic emissions (Harrison, 1982; Boubel et al., 1994). In South Africa H_2SO_4 processes are listed in terms of the second schedule of the APPA and such plants must be operated in compliance with the conditions of a valid APPA registration certificate (RC). Not only does AGA's sulphuric acid production contribute to high SO_2 emissions in the Vaal River area but a number of large industrial processes in Rustenburg contribute to elevated SO_2 concentrations in the region (Table 1.1) (Steyn, 2005). Air pollution control measures applied recently by these and other industries (including AGA), have significantly reduced emissions (Figure 1.3), and this occurred whilst some of the industries had increased their production[2] (Potgieter and Bryszewski, 2005).

[2] The percentage improvements on the graphs should be interpreted as follows:

- all improvements are relative to the status in 2000;
- an improvement in the control of a pollutant, will be an increase in % improvement and *vis-à-vis*;
- an improvement will be seen if:
    - less pollutant is emitted per a fixed quantity of product; or
    - more product is produced, but the quantity of the pollutant emitted does not increase (Potgieter and Bryszewski, 2005)

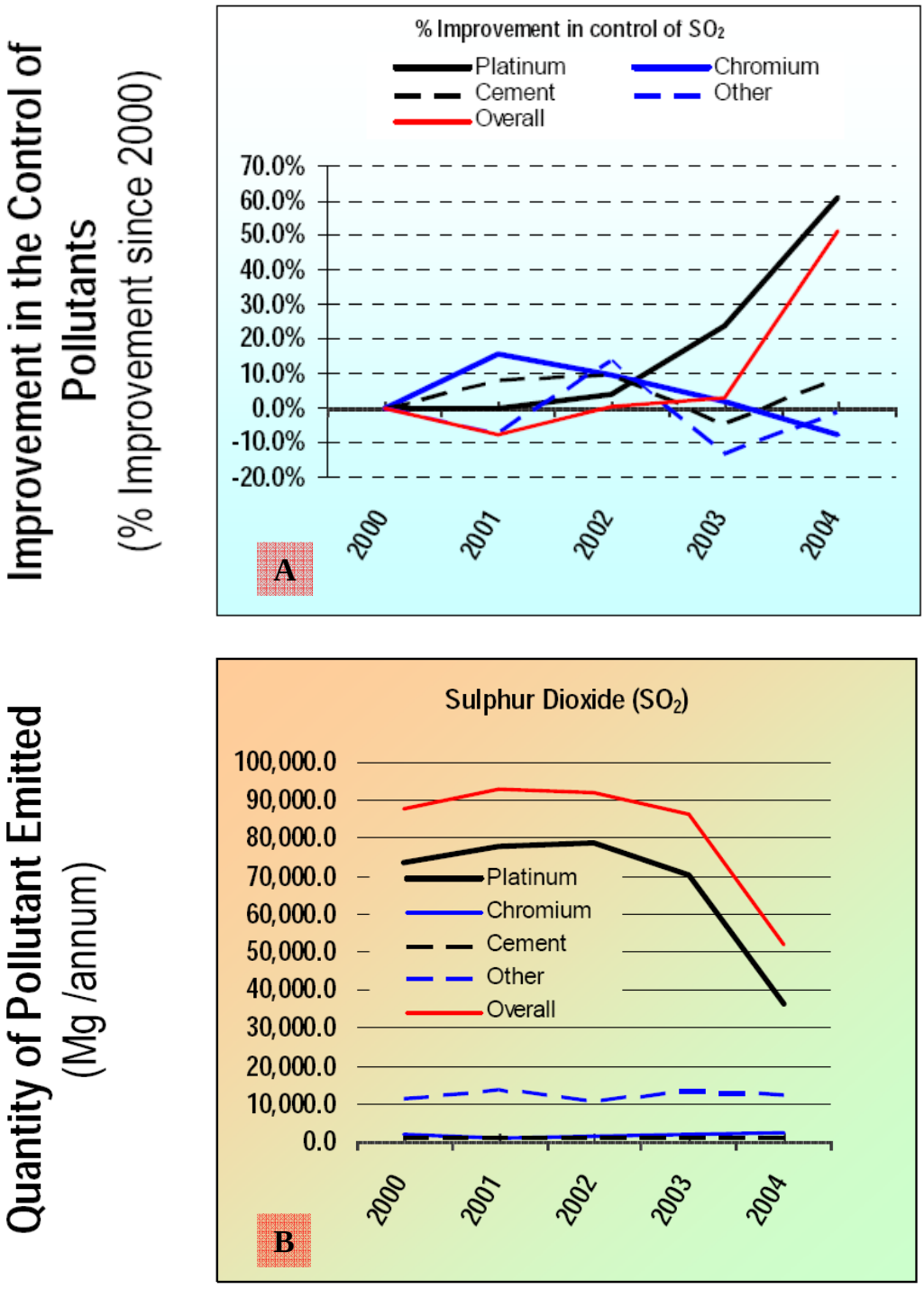

Figure 1.3: Improvement in the control of SO_2 emissions (**A**) and change of quantity of SO_2 emitted by the Overall Province's Scheduled Processes in the North West Province (**B**), for the period 2000 through 2004 (after Potgieter and Bryszewski; 2005). AGA's East Acid Plant emissions are embedded within the **Other** category

Table 1.1: Estimated emission source contributions in the Rustenburg area (Pulles et al., 2001 as cited in Steyn, 2005)

Sulphur dioxide	Oxides of nitrogen	Suspended particulates	
Large industrial (99.25%)	Domestic (65.83%)	Unpaved roads (62.14%)	Domestic (1.54%)
Domestic (0.41%)	Large industrial (25.98%)	Large industrial (28.55%)	Veld fires (1.27%)
Small boilers (0.31%)	Exhaust (6.46%)	Paved roads (3.47%)	Tailings dams (0.45%)
Exhaust (0.03%)	Small boilers (0.99%)	Small boilers (2.26%)	Urban unpaved roads (0.20%)
	Veld fires (0.75%)		Exhaust (0.13%)

By and large many of the industries operating currently are aging and some use less effective air pollution abatement technologies. Most of these plants operate under the old APPA certificates, for example AGAs East Acid Plant operated with a registration certificate dated 1979 until it was renewed in 2005. It is a generic consensus that air pollution impact should be assessed prior to the construction of the plant and/or facility to ensure that efficient air pollution abatement measures are identified and implemented to minimise the level of emissions. However some countries including South Africa have old plants or facilities with less effective air pollution abatement technologies and/or measures. The use of air dispersion models is critical in such cases as they estimate potential air pollution impact from these plants (Buthelezi et al., 2007). It is important to note that, modelling SO_2 concentrations is a complex task which has drawn the attention of many scientists all over the world since the early 1960s. Modelling the dispersion of this pollutant must therefore be executed meticulously to reduce inaccuracy (Nunnari et al., 2004). AGA has identified a dispersion model as an important tool to project air pollution impact from its operations particularly the East Acid Plant and aims at applying the updated versions of AERMOD.

1.4. Research goals

The main objective of this research is to undertake atmospheric dispersion modelling of SO_2 emissions emanating from the AGA's East Acid Plant using a steady-state Gaussian atmospheric dispersion model called AERMOD. An attempt has been made to answer the following research questions:

1. Is comprehensive SO_2 emissions inventory available for successful completion of the research;
2. To what extent does the implementation of the emissions control measures contribute towards positive impacts on the ambient air quality;
3. What is the relationship between emission and monitored ambient air quality data; and
4. Is AERMOD suitable to model or predict the East Acid Plant's SO_2 concentrations.

1.5. Literature review

1.5.1. Air pollution sources and emissions in the Highveld atmosphere

The primary and secondary air pollution is largely caused by the natural and anthropogenically-induced releases e.g. industrial activities largely listed under APPA in a South African context. In the heavily industrialised *'hot spots'* such as the Highveld region and South Durban Industrial Basin, industrial sources are major contributors to the deterioration of air quality (Matooane and Diab, 2001). South Africa's abundance of mineral resources e.g. gold, platinum and coal has for many years led to the development of mining activities mainly in the Mpumalanga and North West provinces where AGA's East Acid Plant is situated. Other associated industry sectors that have developed in sync with the mining industry include Steel, Power Generation and Petrochemical. These sectors have been identified as important sources of air pollution. The dominant pollutants of concern (in addition to SO_2) in the country's air quality hot spots, especially Highveld region are indicated in Figure 1.4.

Domestic fuel (coal) burning is also a considerable contributor to significant low-lying concentrations of sulphur dioxide (SO_2) and particulate matter (PM). Domestic use of solid fuels and heavy industrial activities in the Highveld has led to the high emission density of SO_2. Annegarn et al. (1996), points out that, accompanying the industrial development particularly in the Highveld are environmental impacts, and of particular concern in this case is the spatial and temporal distribution of pollutants into the atmosphere (Annegarn et al., 1996).

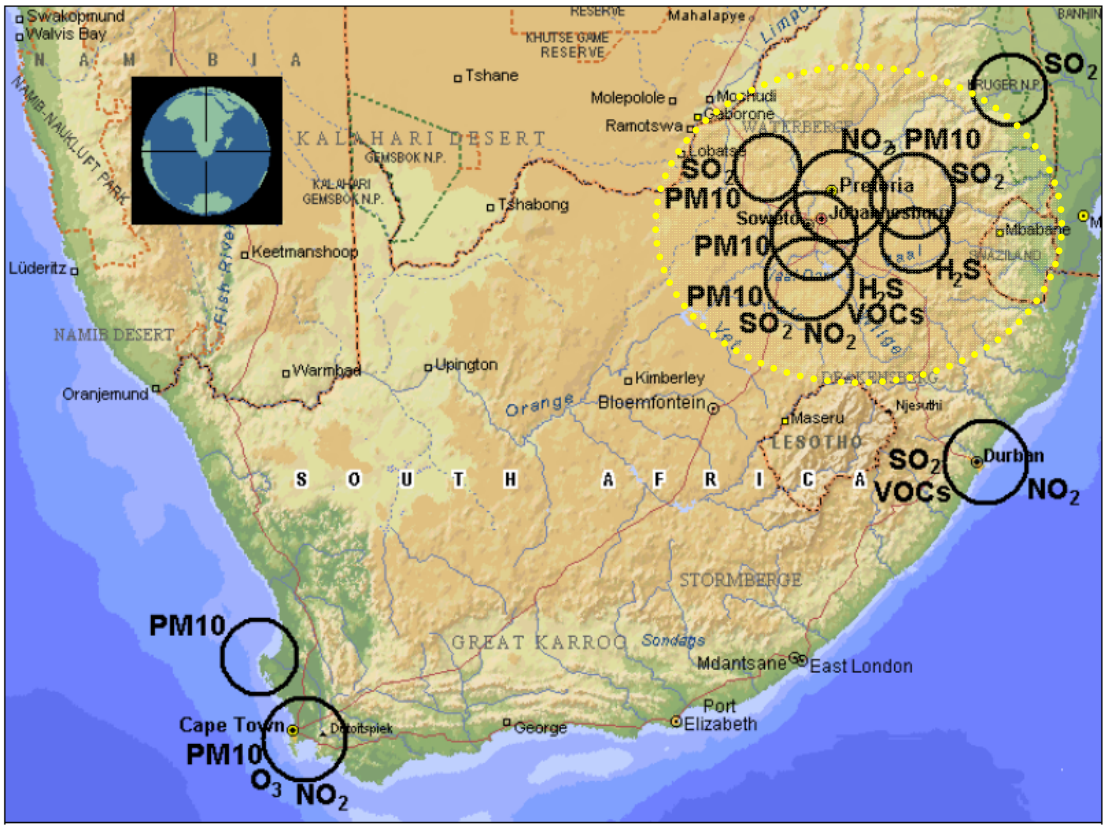

Figure 1.4: South African air quality *hot spots* where elevated air pollutant concentrations in excess of health thresholds have been noted to occur. Indicates the Highveld region which encompasses the North West province where AngloGold Ashanti's East Acid Plant is located (DEAT, 2006)

1.5.2. Dispersion potential of air pollutants in the atmosphere

Atmospheric processes play a significant role in the transportation, transformation and dispersion of air pollutants. This is apparent where aerosols and trace gases transport patterns vary with atmospheric circulation type throughout the year as indicated in Figure 1.6 (Tyson et al., 1996). These transport patterns are controlled by the occurrence of persistent stable stratification at preferred levels in the lower and middle troposphere (Cosjin and Tyson, 1996). Zunckel et al. (2000: 2798) indicate that 'little of the transport takes place to the Atlantic Ocean, whereas more than 75% of all transport over the subcontinent is to the Indian Ocean and beyond' (Figure 1.6). It is thus critical to fully understand the macro-scale, meso-scale and local boundary layer considerations in characterisation of the atmospheric dispersion potential of study area/region (Held et al., 1996b; Baumbach, 1996; Liebenberg-Enslin et al., 2007).

Different Highveld areas are known to share similar characteristics of the boundary layer which when very stable during the long winter nights creates adverse conditions for the dispersion of low-level emissions as turbulent mixing in the vertical is inhibited (Held et al., 1996b; Freiman and Tyson, 2000). The effects of pollutant accumulation are evident to the naked eye at the 700 hPa and 500 hPa levels over the interior of South Africa (Freiman and Tyson, 2000). These scenarios have potential negative impacts on sensitive receptors residing in low lying areas and close to facilities experiencing high fugitive emissions and elevated inversion layers. The North West province particularly the Vaal River and Rustenburg areas is characterised by poor atmospheric dispersion potential for a substantial portion of the year. Sensitive receptors are thus susceptible in these areas. It is therefore important to understand meteorological conditions in these areas to ensure that emissions from the various sources are effectively assessed and managed to minimise potential negative impact on the sensitive receptors.

Situated in the subtropical high pressure belt, southern Africa is influenced by anticyclonic general circulation over the subcontinent which is generally above 700 hPa

and dominated by three high pressure (HP) cells, namely the: 1) South Atlantic HP off the west coast, 2) South Indian HP off the east coast, and 3) Continental HP over the interior (Preston-Whyte and Tyson, 1988; Preston-Whyte and Tyson, 2000; Held et al., 1996b; Piketh et al., 1999; Liebenberg-Enslin et al., 2007). Five major synoptic scale circulation patterns dominate southern Africa as indicated in Figure 1.5.

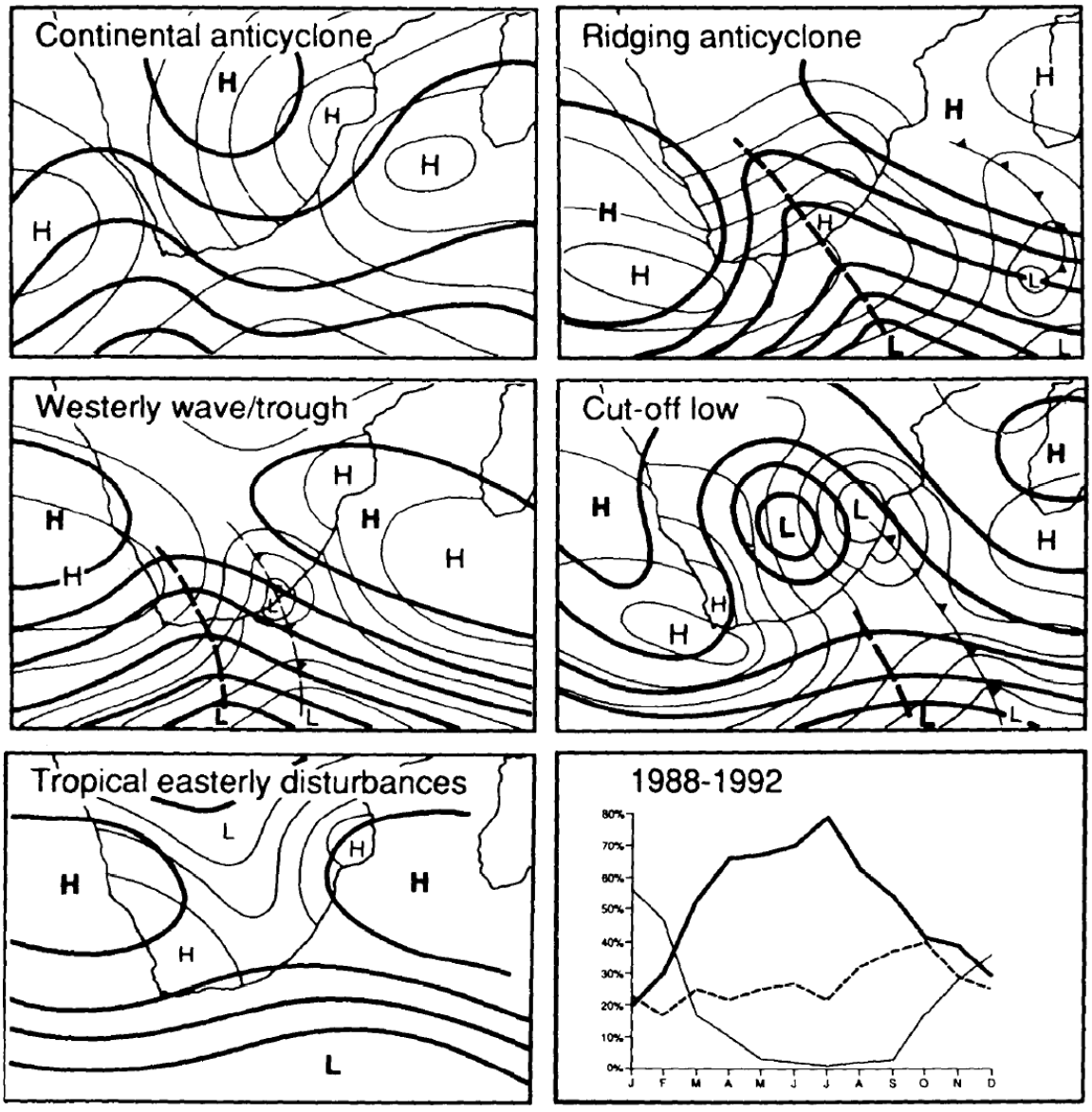

Figure 1.5: Major synoptic circulation types affecting southern Africa and their monthly frequencies of occurrence over a five year period (1988-1992) (after Preston-Whyte and Tyson, 1988)

The frequency of anticyclonic circulations and associated large-scale atmospheric subsidence and surface divergence occur 70% of the time during winter and 20% of the time in summer (Figure 1.6). The resultant effect is the formation of extremely stable atmospheric conditions which can persist at various levels in the atmosphere for long periods (Figure 1.6) (Tyson, 1986 as cited in Held et al., 1996a; Liebenberg-Enslin et al., 2007). Stable layers associated with such stable atmospheric conditions in regions like North West lead to high levels of air pollution due to the inhibited vertical transportation of pollution. As a result pollutants are concentrated below the inversion layers and these inversions play an important role in controlling the long-range transport and recirculation of pollution (Baumbach, 1996; Tyson et al., 1996 as cited in Freiman and Tyson, 2000; Zunckel et al. 2006; Liebenberg-Enslin et al., 2007).

Regional-scale circulation and local conversion amongst other influences have shown to lead to an accumulation of ground-level sulphate concentrations in the Highveld (Held et al., 1996b). This phenomenon is attributed to the subsiding air which warms adiabatically to temperatures in excess of those in the mixed boundary layer. The elevated inversion marks the boundary between the subsiding air and the mixed boundary layer. Protracted periods of anticyclonic weather, such as characterising the plateau during winter, result in persistent inversions which are continuous over considerable distances (Liebenberg-Enslin et al., 2007). However, the development of inversions can be deterred by the convective activity associated with westerly and easterly wave disturbances. The elevated inversions can either be destroyed, weakened or their altitude increased due to cyclonic disturbances which are associated with strong winds and upward vertical air motion (Preston-Whyte and Tyson, 1998; Liebenberg-Enslin et al., 2007). Low-level emissions from the domestic coal burning contribute to concentrations in the immediate vicinity of the source under stable nocturnal conditions; however these sources do not contribute to high regional concentrations (Annegarn et al., 1996).

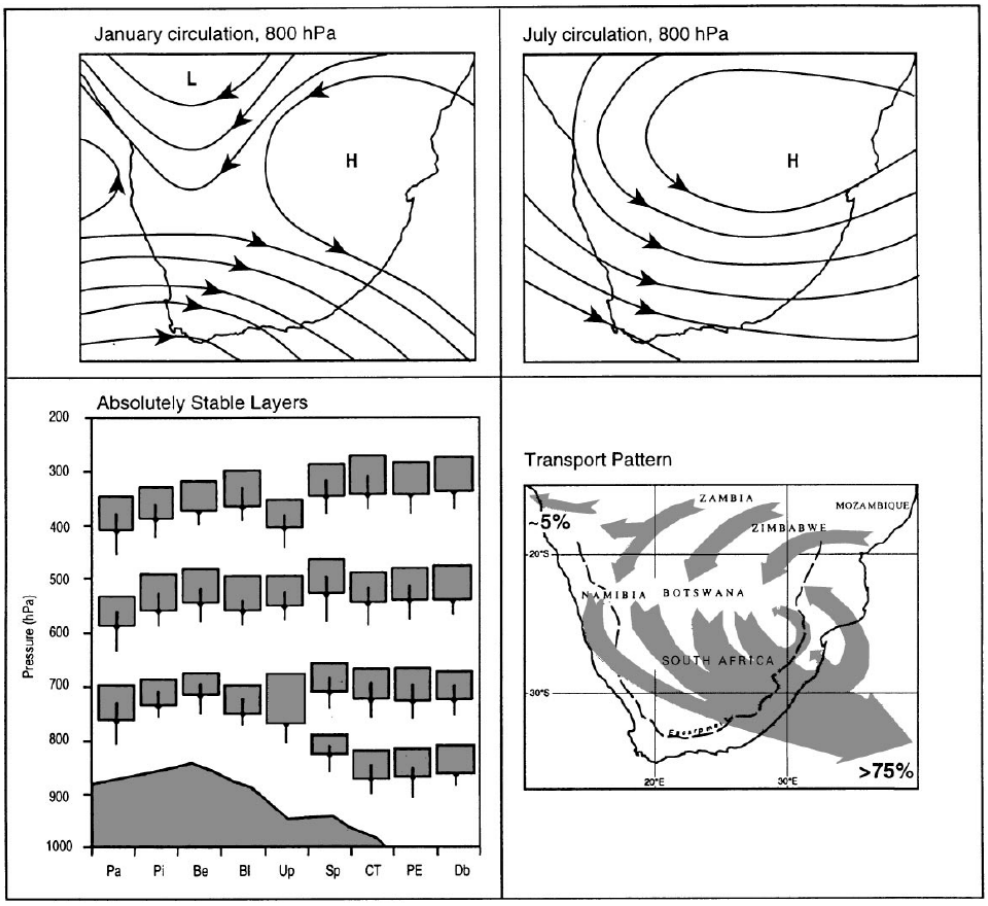

Figure 1.6: Mean 800 hPa circulation over southern Africa in summer and winter (after Tosen and Jury, 1986), temporarily consistent absolutely stable layers over southern Africa (after Cosjin and Tyson, 1996) and major transport pathways over southern Africa (after Tyson and Preston-Whyte 2000)

1.5.3. Atmospheric dispersion modelling

Atmospheric dispersion modelling is a method of predicting the ambient impact of one or more sources of air pollutants. The algorithms used in the models are based both on the known physics of atmospheric processes (meteorological data) and on empirical data (pollutant emission rate). Such information is used by the model to mathematically simulate (or project) the pollutant's downwind dispersion in order to derive estimates of concentration at a specified location (usually a receptor site). Some dispersion models

even simulate the chemical transformations and removal processes that can occur along the transport path. The results of such analysis can for example be used by the regulatory authorities to determine if a new or existing source of air pollutants can comply with authorities' maximum ambient concentration limits (Boubel et al., 1994; Oklahoma Department of Environmental Quality, 2006).

Atmospheric dispersion models, emission inventories and other related methods (Figure 1.7) have over the years gained popularity as practical/effective air quality management tools. These tools have largely been applied by industries and/or state departments in developed countries and lately developing countries (e.g. South Africa) to establish air quality management programmes, for example. McVehil et al. (2001:3) points out that 'if new regulations are to be effective and appropriate, it is essential that potential impacts of existing and new mining operations are quantified as realistically as possible. The meaningful evaluation of future impacts is essential both for public policy development and for development of any mitigating measures that may be necessary'. In essence a sound air quality management strategy is necessary to address all air emissions and their relevant impact on the environment. To that effect air pollution modelling is a fundamental part of such a sound air quality management strategy as it aims at determining the relative impact of industries (sources) on the receiving environment of which the Air Quality Act, 2004 focuses on. However, these models must be conscientiously applied as the performance of various models in the South African Highveld conditions has not been well established. It is for this reason that local validation needs to be pursued in order to guarantee improved performance for South African Highveld conditions considering the extremes of stability over this region (Turner, 1996, Ross et al., 2006). The model performance evaluation is undertaken in this study and discussed in chapter three of this report.

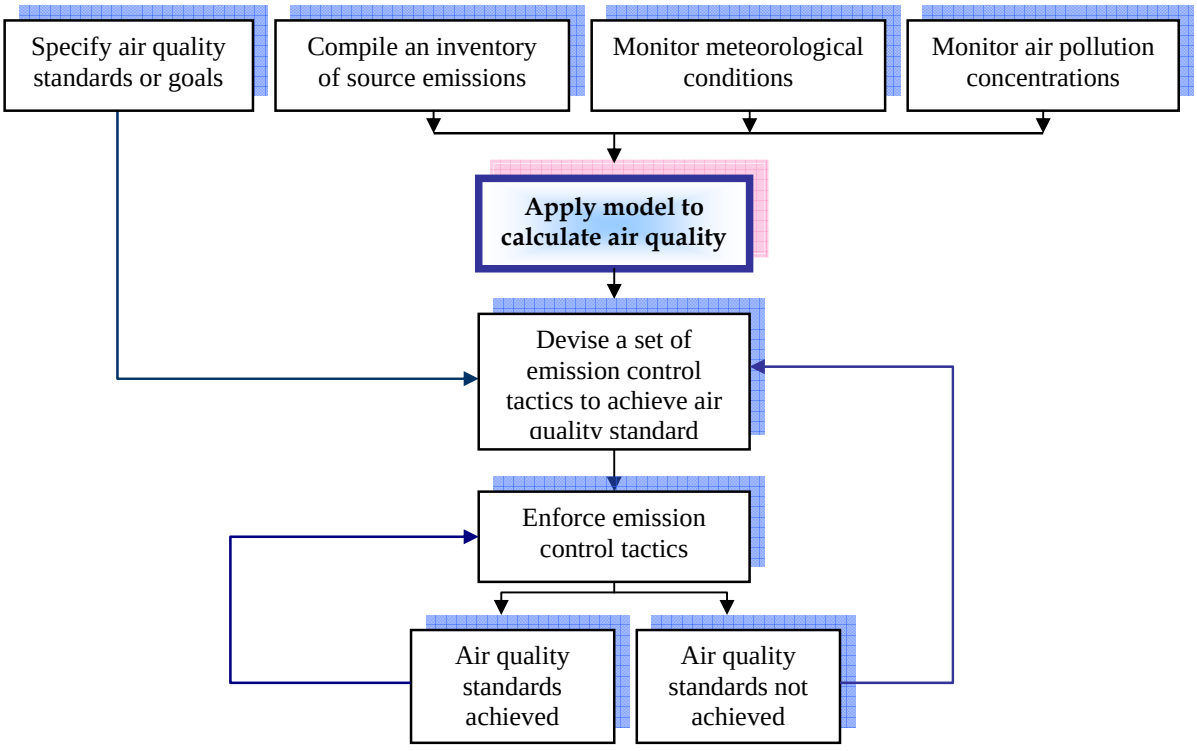

Figure 1.7: Stages involved in the development of air quality management strategy (after WHO, 2000)

Furthermore, according to Seinfeld (1975); Zannetti, (1993); New Zealand Ministry for the Environment (2004); Annegarn et al. (2006) air dispersion model applications include:

- Establishing emission control legislation; i.e. determining the maximum allowable emission rates that will meet fixed air quality standards and emission limits;
- Evaluating proposed emission control techniques and strategies; i.e. evaluating the impact of future abatement and mitigation control options;
- Selecting locations of future sources of air pollutants, in order to minimise their environmental impacts;
- Planning the control of air pollution episodes; i.e., defining immediate intervention strategies, (i.e. warning systems and real-time short-term emission reduction strategies) to avoid severe air pollution episodes in a certain region;

- Assessing responsibility for existing air pollution levels; i.e. evaluating present source-receptor relationships;
- Buffer zone delineation, and
- Integral component of air quality management and planning.

Air pollution knows no boundaries and the pollutants can disperse and reach locations distant from the original source. It is thus important that air dispersion modelling consider the scale of the modelling domain to ensure that a correct model is applied and the following carefully considered:

a. Gaussian models (applied in this study) are the most widely used techniques for estimating the impact of non-reactive pollutants, or pollutants being treated as non-reactive. These models are based on the assumption that the plume concentration at each downwind distance has independent Gaussian distributions both in the horizontal and in the vertical axis, thus the Gaussian formula (below) will describe a three dimensional concentration field generated by a point source under stationary meteorological and emission conditions:

$$\chi_{(x,y,z)} = \frac{Q}{2\pi\sigma_y\sigma_z U}\exp\left[-\frac{y^2}{2\sigma_y{}^2}\right]\left\{\exp\left[-\frac{(z-H_e)^2}{2\sigma_z{}^2}\right]+\exp\left[-\frac{(z+H_e)^2}{2\sigma_z{}^2}\right]\right\}$$

where,

$\chi(x,y,z)$ = concentration ($\mu g.m^{-3}$) at distance x downwind, distance y across wind, and at height z above ground
U = wind speed ($m.s^{-1}$)
σy and σz = standard deviations of lateral and vertical concentrations (i.e. dispersion parameters)
He = effective stack height (m)
Q = emission rate ($g.s^{-1}$)

b. Numerical models may be more appropriate than Gaussian models for area source, urban and industrial applications that involve reactive pollutants, but they require much more extensive input databases and resources. Some of the numerical model types include:

i. Plume-rise models calculate the vertical displacement and general behaviour of the plume in its initial dispersion phase,
ii. Eulerian models numerically solve the atmospheric diffusion equation i.e. equation for conservation of mass of the pollutant (Eulerian approach), and
iii. Lagrangian models describe fluid elements that follow the instantaneous flow of air. They include models in which plume rise is broken up into elements such as segments, puffs or particles.

c. Semi-empirical / Statistical models are characterised by drastic simplifications and a high degree of empirical parameterisations. Statistical or empirical techniques are frequently employed where incomplete scientific understanding of the physical and chemical processes, or lack of the required databases make the use of a Gaussian or numerical model impractical.

d. Physical modelling involves the use of wind tunnel or other fluid modelling facilities. This class of model is complex and its processing requires a high level of technical expertise, as well as access to the necessary facilities. Nevertheless, physical modelling may be useful for complex flow situations, such as the building, terrain or stack downwash conditions, plume impact on elevated terrain, diffusion in an urban environment, or diffusion in complex terrain.

e. Receptor models, in contrast to the dispersion models (which compute the contribution of a source to a receptor as the product of the emission rate multiplied by a dispersion coefficient), start with observed concentrations within a receptor and seek to apportion the observed concentrations at a sampling point among several source types. This is done based on the known chemical composition of source and receptor materials. Receptor models are based on mass-balance equations and are intrinsically statistical in that they do not include a deterministic relationship between emissions and concentrations.

(Guideline on Air Quality Models (Revised), 1991; Cheremisinoff, 1993; Beychok, 1994; New Zealand Ministry for the Environment, 2004; Hurley, 2005; Yarmatino, 2008).

As observed in the above section, various models have been developed, each designed to meet a specific application or need. The application of these models on particular scenarios is further dependent on their scale and complexity as indicated in Figure 1.8. The AERMOD, Californian Puff Model (CALPUFF), Advanced Dispersion Modelling System (ADMS), and ISCST3 are USEPA's preferred and commonly used dispersion models worldwide. These models have also been applied in various South African air quality studies. The models functionality is summarised in Table 1.2 which indicates how AERMOD (applied in this study) compare against other dispersion models.

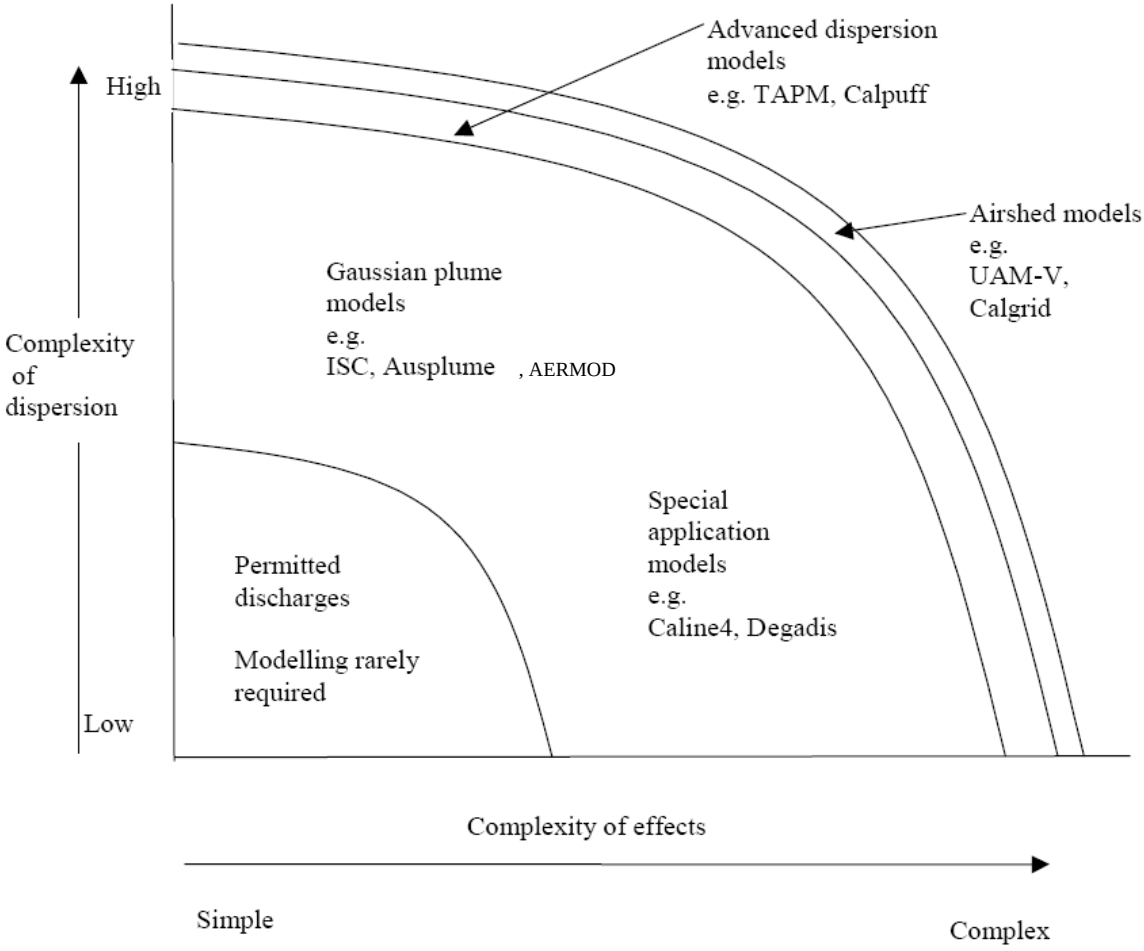

Figure 1.8: Type of model typically applied according to the complexity of the problem. In medium-complex atmospheric and topographical conditions with relatively simple effects, Gaussian-plume models can produce reliable results. In more complex conditions, advanced puff or particle models and meteorological modelling may be required to maintain a similar degree of accuracy (New Zealand Ministry for the Environment, 2004)

Table 1.2: Comparison of ISCST3, AERMOD, CALPUFF and ADMS air dispersion models (Hanna et al., n.d., Walker et al., n.d.)

Model	Functionality
ISCST3	ISCST3 is a straight line trajectory model, based on a steady-state Gaussian plume algorithm. It is applicable for estimating ambient impacts from point, area, and volume sources to a distance of about 50 kilometres in a simple terrain. ISCST3 includes algorithms for addressing building downwash influences, dry and wet deposition. This model utilises hourly meteorological data that have been pre-processed using the PCRAMMET. This model can also be used as a screening model to determine whether more advanced modelling is required. The major advantages of ISCST3 over models like AERMOD and ADMS are its relative simplicity of use and its robust predictions (i.e., the same results can be obtained by different users for the same scenario). The amount of meteorological input data required by ISCST3 is relatively small, and the model can be run sequentially with routinely collected airport data. For a single meteorological condition for a passive pollutant, the meteorological data needed are a single wind speed, a wind direction, a stability class determination, and an assumed mixing depth. Terrain elevations at receptor points, building dimensions in addition to emissions and stack parameters are also needed. The disadvantages of ISCST3 are largely associated with the fact that an improved knowledge of the structure of the atmospheric boundary layer and resulting estimations of turbulent dispersion processes cannot be accommodated in this model.
AERMOD	AERMOD is a steady state plume dispersion model built on the ISCST3 framework. It incorporates air dispersion based on planetary boundary layer (PBL) turbulence structure and scaling concepts including treatment of both surface and elevated sources, and both simple and complex terrain. These algorithms are similar to those of ADMS. AERMOD contains two pre-processors for meteorology (AERMET) and terrain (AERMAP). AERMOD is also able to account for building downwash and modelling of odour compounds. AERMOD is however limited in its capability to treat atmospheric chemical processes and odours are not explicitly part of the model. There are no specific processes included for treating ammonia or hydrogen sulphide. Only reactions including SO_2 are modelled using a simple chemistry scheme. AERMOD also produce conservative results for short (<100 m) or low-level sources. Overseas validation show that this model is more likely to over- rather than under-predict ground-level concentrations, which offers some degree of safety in the regulatory environment when assessing discharges from short or low-level sources. Additional technical aspects are discussed in chapter two of this report.

Model	Functionality
CALPUFF	CALPUFF is an integrated, multi-layer, multi-species non-steady-state puff model. It is applied for long-range impacts (> 50 km), visibility (light extinction), and acid deposition. CALPUFF requires more sophisticated meteorological data inputs than other models such as ISCST3. This model includes a complex terrain algorithm to account for the effect of elevated terrain on ground level concentrations, and a shoreline model to account for the formation of a thermal internal boundary layer (TIBL) due to land-water temperature differences. CALPUFF can model continuous or time varying releases from point, line, area and volume sources. This model includes similar physics as AERMOD and can handle various types of complex terrain including mountain areas and shoreline environments. The results of CALPUFF are known to be similar to AERMOD and better than ISCST3. As an advanced dispersion model, CALPUFF is data intensive and requires more expertise and resources than the above mentioned models.
ADMS	ADMS is an advanced steady state, Gaussian-like dispersion model capable of simulating continuous plumes and short duration puff releases. The model can be applied to point, line, area and volume sources and has a module applicable to motor vehicle emissions. Unlike other freely downloadable modes, it is a proprietary model and therefore needs to be licensed for commercial applications. Improvements to the model over ISCST3 are most evident in the treatment of dispersion rate variations within the atmospheric boundary layer. In this regard it is similar to AERMOD. Verification of the model has been partially based upon the Kincaid and Indianapolis data bases, which were also used to verify AERMOD. ADMS compare well with AERMOD in the treatment of dispersion and complex effects, and provides a variety of other options that are unavailable in AERMOD (short term fluctuations for odours, condensed plume visibility, puff release, and special treatment for coastline area). ADMS is one of the few models classified as user friendly. Nonetheless, the potential costs involved for both software and training may limit accessibility of this model.

1.5.4. Emission factors (EFs)

Emission factors (EFs) and emission inventories have long been fundamental tools for air quality management. Emission estimation techniques are important for developing emission control strategies, determining applicability of permitting and control programs and ascertaining the effects of sources and appropriate mitigation. Data from source-specific emission tests or continuous emission monitors such as that of the East Acid Plant are usually preferred for estimating a source's emissions because they provide the best representation of the tested source's emissions. However, test data from individual sources are not always available and, even then, they may not reflect the variability of actual emissions over time. Thus, emission factors are frequently the best or only method available for estimating emissions, in spite of their limitations (USEPA, 1995).

An emission factor can be defined as a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant. Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category (USEPA, 1995; Environment Australia, 2001). A general equation for emission estimation is depicted as follows:

$$E_{kpy,i} = [A * OpHrs] * EFi * [1-(CEi/100)]$$

Where

$E_{kpy,i}$	=	emission rate of pollutant i, kg/yr
A	=	activity rate, t/hr
OpHrs	=	operating hours, hr/yr
EFi	=	uncontrolled emission factor of pollutant i,kg/t
CEi	=	overall control efficiency for pollutant i,%

1.5.5. Sulphur dioxide (SO_2) and its health effects and environmental impacts

1.5.5.1. Sulphur dioxide (oxidation and conversion)

A complete combustion of sulphur containing fuels results to the formation of SO_2 according to Eq. (5). Elemental sulphur (S) and hydrogen sulphide (H_2S) are some of the pollutants resultant from the incomplete (oxygen starved) combustion processes as shown by Eqs. (6) and (7).

$$CH_3 - SH + 3O_2 \longrightarrow SO_2 + CO_2 + 2H_2O \quad (5)$$

$$CH_3 - SH + 0{,}5O_2 \longrightarrow H_2S + HCHO \quad (6)$$

$$2H_2S + O_2 \longrightarrow 2H_2O \longrightarrow 2S. \quad (7)$$

(Benítez, 1993; Baumbach, 1996)

In the gas-phase pathway, SO_2 reacts with hydroxyl radicals (OH) in the atmosphere to form H_2S, which sequentially reacts rapidly with oxygen (O_2) and water vapour (H_2O) to form sulphuric acid gas (Watson et al., 1990 as cited in Walton, 2005). SO_2 is partially oxidised to H_2SO_4 prior being deposited in a dry or wet form[3] (Hales, 1978; Saxena and Seigneur, 1987; Pham et al., 1996; Saboni and Alexandrova, 2001; Seinfeld and Pandis, 2006). Sulphuric acid gas forms sulphuric acid droplets in the presence of water, however these processes depend on various factors some not yet comprehensively known. The oxidation of SO_2 by O_2 can be accelerated in polluted air by catalysts such as manganese (Mn^{2+}) and ferrous ions (Fe^{3+}). In less polluted air, SO_2 oxidation is accelerated by oxidising agents such as the ozone (O_3) and hydrogen peroxide (H_2O_2) dissolved in water droplets (Jacob and Hoffmann, 1983; Seigneur and Saxena, 1984; Baumbach, 1996).

[3] *Dry deposition* denotes the direct transfer of gaseous and particulate species to the Earth's surface and proceeds without the aid of precipitation.

Wet deposition encompasses all processes in which airborne species are transferred to the Earth's surface in aqueous form (Seinfeld and Pandis, 2006).

The atmospheric conversion of SO_2 to SO_4^{2-} is attributed to the high soot content in the ambient aerosol particularly in the high polluted regions e.g. Highveld. This process contributes to both $PM_{2.5}$ and PM_{10} concentrations and influence the chemical composition and size distribution of the particulate SO_4^{2-} which in turn impact on visibility and human health (Baumbach, 1996; Eatough et al., 1994 as cited in Walton, 2005). Moreover, the close relationship between OH and photochemistry results to the SO_2 to SO_4^{2-} transformation rate maximised during the day and at night being minimal. This process is prevalent during summer than in winter due to variation in temperatures and conversion rates (Saxena and Seigneur, 1987; Baumbach, 1996; Watson et al., 1990 as cited in Walton, 2005).

1.5.5.2. Health effects

Clean air is essential for the good quality of life and it is important to consider the effects of pollutants (SO_2) on the human health. The impact of air pollutants on the human body is largely dependent on the following factors:

- Toxicity of the individual pollutants,
- Concentration of the pollutants x length of exposure = pollutant dose,
- Combined effect of several pollutants,
- Ambient conditions such as temperature, radiation, air movement, humidity a.s.o, and
- Age and health condition of the individual (Baumbach, 1996).

Various air pollutants are associated with human health impacts and this is the main driver of the setting of ambient standards and emission limits which are based on the epidemiological, clinical and toxicological studies. The comparison of pollutant concentrations with the given maximum values helps determine where protective measures and emission reduction are mainly needed (e.g. setting up air quality management plans) (Baumbach, 1996; Boubel et al., 1994).

SO_2 emitted by AGA's East Acid Plant is a criteria pollutant known to cause bodily harm on human beings at certain concentration levels and has the following health effect related characteristics:

a) Damages human respiratory function and increases prevalence of chronic and risk acute respiratory diseases,
b) Due to its high solubility, SO_2 is likely to be absorbed in the upper airways rather than penetrate to pulmonary region,
c) Sour taste in pure air from 0.23 ppm,
d) Dissolves in mucous membranes of eyes, mouth, nose and bronchi,
e) Levels of 10 ppm cause nosebleeds, 20 ppm irritates eyes, 100 ppm poses immediate danger to life and health (IDLH) and 1000 – 3000 ppm is a lethal concentration for 50% of laboratory animals tested (LC_{50}),
f) It has the lowest adverse effect levels at the following concentrations:
   i. 0.382 ppm – short-term exposure,
   ii. 0.095 ppm – 24 hour exposure.

(Boubel et al., 1994; Baumbach, 1996; Batterman et al., 1999; Annegarn et al., 2006)

1.5.5.3. Environmental impacts

Sulphate particles contribute to reduced visibility and small particles are the main contributors as they are able to remain airborne for longer periods and can travel long distances. SO_2 and nitrogen oxides (NOx) become oxidised to sulphate and nitrate through both gas- and aqueous-phase processes as shown in Eqs. (8) - (11). This reaction is sustained by the atmosphere as it is a potent oxidising medium.

Sulphur dioxide reacts with water to form sulphurous acid (H_2SO_3):

$$SO_2\,(g) + H_2O\,(l) \longleftrightarrow H_2SO_3\,(aq) \quad (8)$$

Sulphur dioxide is gradually oxidised to sulphur trioxide (SO_3):

$$2SO_2\,(g) + O_2\,(g) \longrightarrow 2SO_3\,(g) \quad (9)$$

Sulphur trioxide (SO_3) reacts with water to form sulphuric acid (H_2SO_4):

$$SO_3\,(g) + H_2O\,(l) \longrightarrow H_2SO_4\,(aq) \quad (10)$$

Oxides of nitrogen, particularly nitrogen dioxide (NO_2) react with water to form nitrous acid (HNO_2) and nitric acid (HNO_3):

$$2NO_2\,(g) + H_2O\,(l) \longrightarrow HNO_2\,(aq) + HNO_3\,(aq) \quad (11)$$

(Hobbs, 2000; Seinfeld and Pandis, 2006; ausetute.com, 2007)

SO_2 deposition is a serious factor in metal corrosion, one of the well researched impacts associated with the acidity of sulphur dioxide. Corrosion processes are usually electrochemical in nature and electrochemical corrosion is the main mechanism in iron metals. AngloGold Ashanti's corroded East Acid Plant (Figure 1.9) is a good indication of the impact of SO_2 acidity on the acid plant infrastructure. The high concentrations of sulphur dioxide emissions released from the stack and leaking areas expose roofing and adjoining buildings to very severe corroding conditions as shown on Figure 1.9.

Figure 1.9: Evidence of corrosion as a result of SO_2 acidity at the East Acid Plant's Plate Scrubber (**A**), old Hot Heat Exchanger (HHE) (**B**) and new HHE (**C**)[4]

[4] New Hot Heat Exchanger (HHE) (**C**) plate included to demonstrate distinction between the corroded and new (uncorroded) HHE

Moreover, the natural or cultivated vegetation are exposed to sulphuric acid aerosols directly via the leaves/needles and indirectly via the roots (Manahan, 1994; Baumbach, 1996; van Greunen, 2006). Changes in the physical appearance of vegetation are an indication that the plant's metabolism is impaired by the concentration of sulphur dioxide. This harm can occur within hours or days of being exposed to high levels of sulphur dioxide. The effects of SO_2 is also influenced by other biological and environmental factors such as the plant type, sunlight levels, temperature and the presence of other pollutants i.e. ozone and nitrogen oxides.

Sulphur dioxide also impacts on the climate system. The injection of 20 million tons of SO_2 into the stratosphere during Mt Pinatubo volcanic eruption in 1991 resulted in the hemispheric temperatures dropping by 0.2-0.5^{o}C for a period of 1-3 years. This has served as a catalyst for more research currently undertaken to probe the degree of climate change due to SO_2 derived cloud condensation nuclei (CCN) concentrations (Wigley, 1989; Uherek, 2007). The negative impacts of SO_2 both on human health and natural environment are widely known as indicated in the section above. It is therefore important to effectively manage SO_2 emitting sources especially in South Africa where major industries rely on fossil fuels e.g. coal and have been operating on outdated air quality permits.

1.5.6. Overview of the Acid Plant modelling study

Near-ground air pollutant concentrations occurring as a result of the East Acid Plant and the now inoperative West Acid Plant (WAFU) atmospheric emissions were simulated by Scorgie and Venter in the 2004 air quality study. This study aimed at determining the Acid Plant's compliance with the ambient air quality limits and health effect screening levels. The air dispersion modelling source input parameters were collated, viz. source heights, stack diameters, efflux velocities and gas exit temperatures. Hourly average meteorological data for at least one full year was also prepared for input in the air dispersion simulations and the widely-used US-EPA ISCST3 model was applied.

The modelling results indicated that neither the Acid Plants were found to comply with the DEAT permit requirements, nor be within best practice emission guidelines[5]. Maximum 10-minute, 1-hour, 24-hour and annual average sulphur dioxide (SO_2) concentrations predicted to occur exclusively due to the Acid Plant stack emissions are illustrated in Figure 1.10 and Figure 1.11 respectively[6]. Sulphur dioxide guideline exceedances were predicted to occur for 10-minute, 1-hour and 24-hour averaging periods. The frequency of exceedance of the European Commission's (EC) hourly SO_2 guideline was also identified in the model results. The TARA short term effect screening level for sulphur trioxide (SO_3) was predicted to be exceeded and the frequency of exceedance is depicted in Figure 1.12 (Scorgie and Venter, 2004b). Following the identification of non-compliances, AGA reviewed the West and East Acid Plant operations with a view to improve the conversion efficiencies and significantly reduce stack and fugitive emissions. A number of interventions for the East Acid Plant have since been implemented as indicated in Section 1.7 below.

[5] **Bold** isopleth plots indicate S.A. guidelines for sulphur dioxide

[6] It should be noted that the isopleth plots reflecting 1-hour and 24-hour averaging periods contain only the highest predicted ground level concentrations, for those averaging periods, over the entire period for which simulations were undertaken. It is therefore possible that even though a high hourly (daily) average concentration is predicted to occur at certain locations, that this may only be true for one hour (day) during the year (Scorgie and Venter, 2004a).

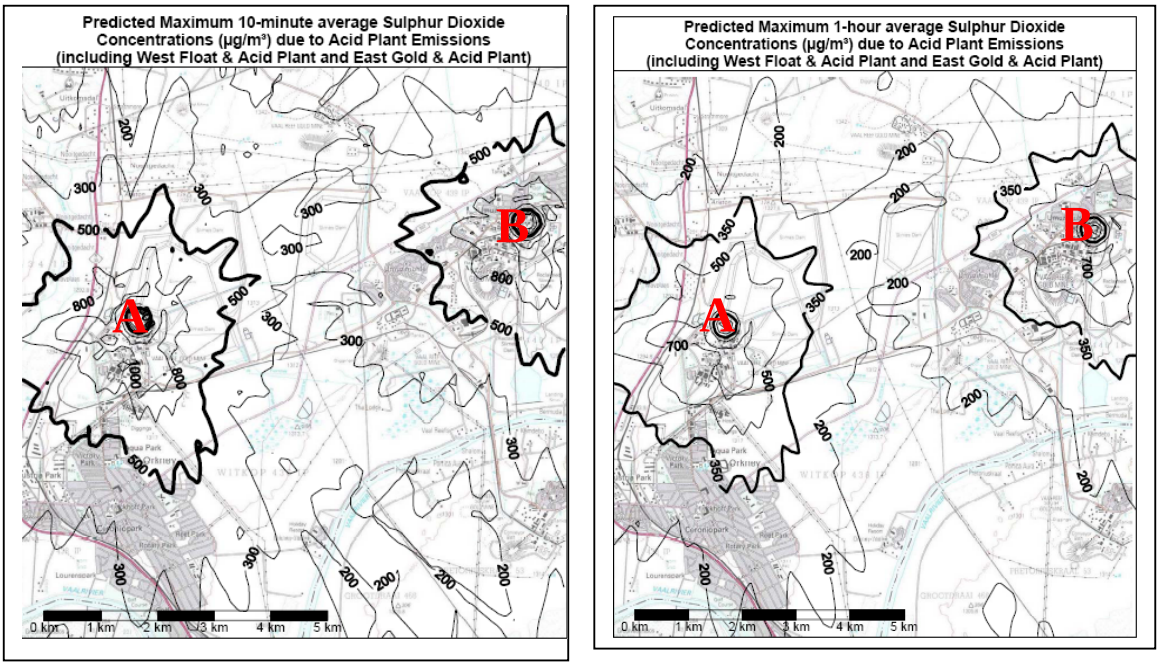

Figure 1.10: Predicted maximum 10-minute (left) and 1-hour (right) average acid plants stack SO_2 concentrations. The S.A guideline and EC limit for these averaging periods is 500 µg.m^{-3} and 350 µg.m^{-3} (Scorgie and Venter, 2004a). **A** – West Acid Plant, **B** – East Acid Plant

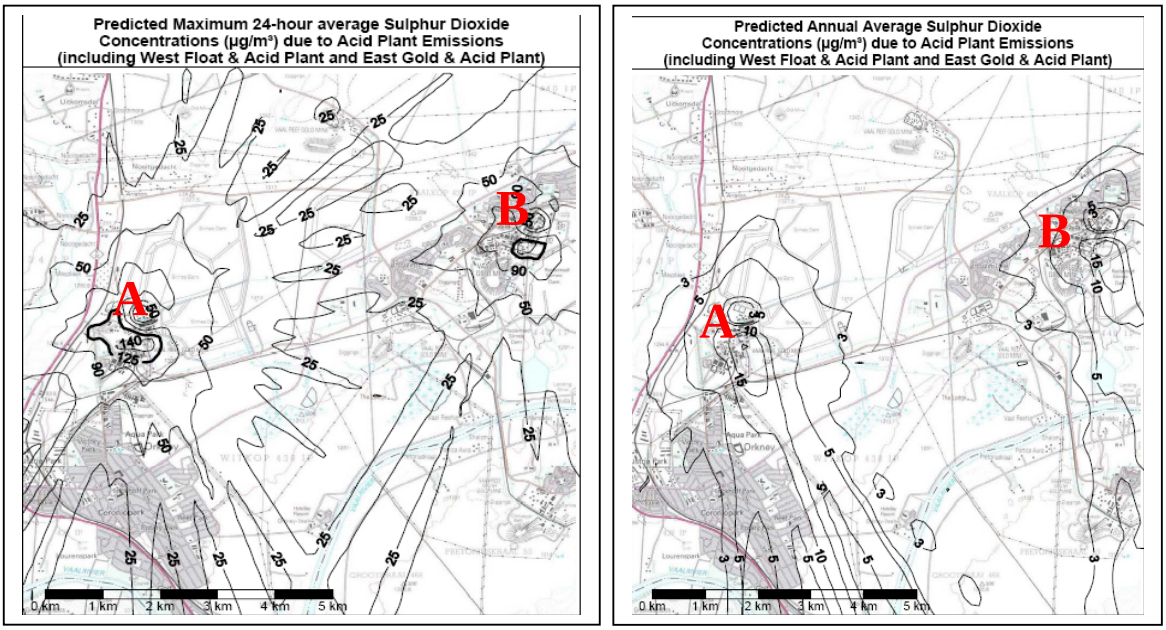

Figure 1.11: Predicted maximum 24-hour (left) and annual (right) average acid plants stack SO_2 concentrations. The S.A guideline for daily averaging period is 125 µg.m^{-3} and annual guideline is 50 µg.m^{-3} (Scorgie and Venter, 2004a). **A** – West Acid Plant, **B** – East Acid Plant

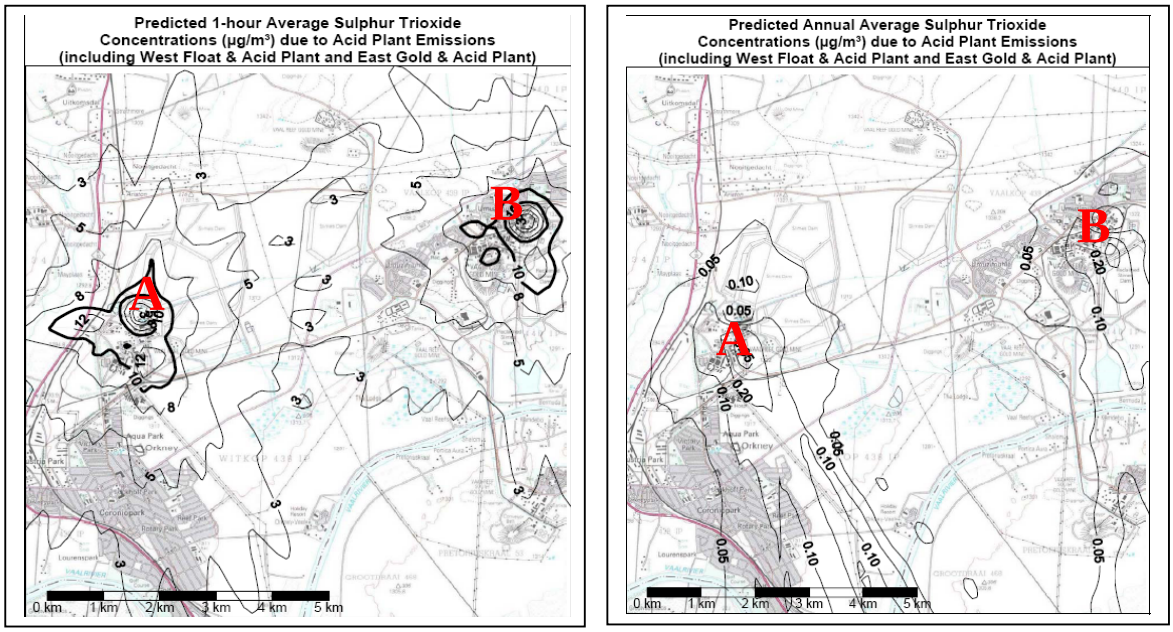

Figure 1.12: Predicted maximum 1 hour (left) and annual (right) average sulphur trioxide concentrations occurring due to acid plants stack emissions. The TARA short term effect screening level is 10 µg.m^{-3} and the long term effect screening level is 1 µg.m^{-3} (Scorgie and Venter, 2004a). **A** – West Acid Plant, **B** – East Acid Plant

1.6. Air pollution sources at AngloGold Ashanti's Vaal River operations

Air pollution sources contributing to SO_2 concentrations in the Vaal River area were identified and modelled in this study. The identified sources (Figure 1.13) include volume and point sources within the Great Noligwa No. 8 Gold Plant, South Uranium Plant and the East Acid Plant, acknowledged to be a major contributor to SO_2 emissions. This modelling exercise is limited to the above mentioned sources (Figure 2.2), although it is recognised that SO_2 emissions from other sources such as the medical waste incinerator, small industrial activities and townships will influence the local air quality.

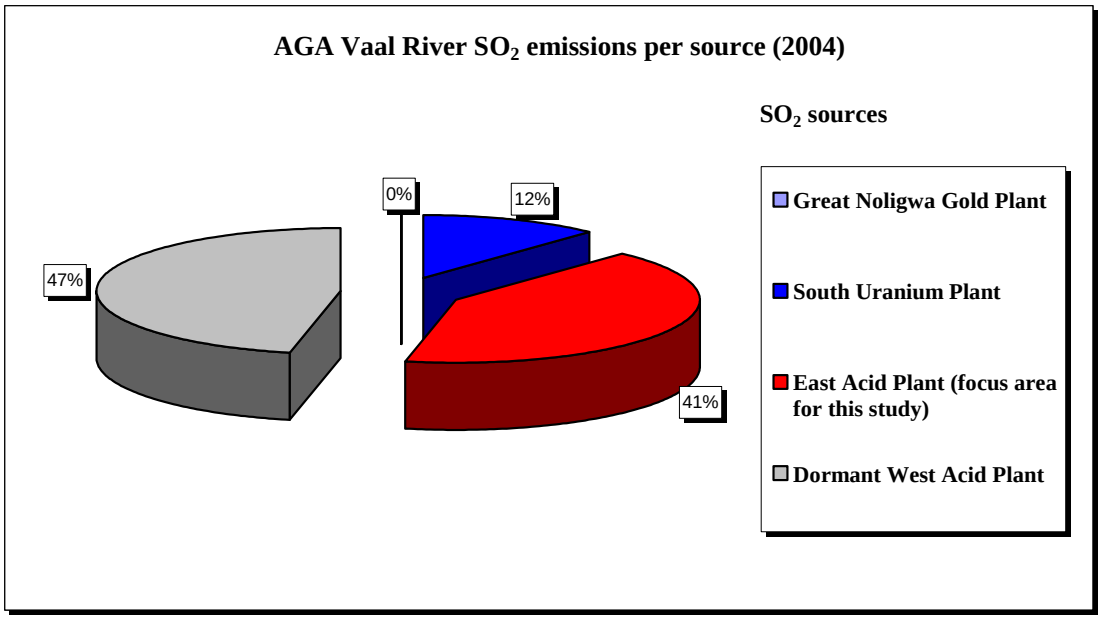

Figure 1.13: AngloGold Ashantis' SO_2 emissions per source as identified in 2004 (Scorgie and Venter, 2004b)

Great Noligwa No. 8 Gold Plant is situated within the Great Noligwa mine, adjacent to the South Uranium Plant (Figure 1.14 and Figure 2.2). This plant recovers gold from the ore and has a conventional crushing, screening, semi-autogenous grinding and carbon in leach (CIL) processes, which are followed by milling and treatment (Smith, 2002). Sources emitting SO_2 within this plant comprise of a smelter bag houses, calcine furnace at wall outside furnace building, sample preparation area and electrowinning cell extractor.

Figure 1.14: Great Noligwa No. 8 Gold Plant site. Areas shown in this figure include the Run of Mine ore screening and washing area (A) and the furnace building (B)

The South Uranium Plant (Figure 1.15) commissioned in 1979 recovers gold and extracts uranium in pulp. This is undertaken through numerous processes entailing leaching, counter current decantation, counter current ion exchange (CCIX), solvent extraction, uranium precipitation and gold removal from CCIX resin (Smith, 2002). Sources emitting SO_2 in the uranium plant comprise of ammonium di-uranate (ADU) and boiler stacks.

Figure 1.15: South Uranium Plant site. Areas shown in this figure include the six counter current decantation thickeners, boiler stack (A) and the recently commissioned ambient air quality monitoring station (B)

The East Acid Plant (Figure 1.1) facilitates gold extraction from pyrite and produces sulphuric acid as indicated in the acid production section above. East Acid Plant together with the now inoperative West Acid and Floatation Plant (WAFU) (Figure 1.16) were identified by Scorgie and Venter (2004a) modelling study as important sources of sulphur dioxide emitted via the stacks and fugitive sources such as the calcine effluent sumps and calcine thickeners.

Figure 1.16: Inoperative West Acid and Floatation Plant (WAFU) site. Areas shown in this figure include the flotation and acid plant area, stack (A) and the meteorological station (B)

1.7. Air pollution control measures implemented in 2007 at the East Acid Plant

A number of additional air pollution control measures have been implemented at AGA's East Acid Plant, to improve operational and environmental performance and monitoring. More capital is being allocated to plant repairs, added to which major maintenance now takes place annually instead of every two years. Extensive repairs worth R15 million were conducted on the plant in August 2007 and this is R9 million more than the previous (2006) biennial shutdown. Work undertaken during the August 2007 shutdown comprised:

a. Replacement of the hot heat exchanger (HHE);

b. Repair to the converter;
c. Rebuilding of the No. 2 roaster refractory lining; and
d. Increased sulphuric acid conversion efficiency.

1.8. East Acid Plant mass balance and monitored ambient SO_2 concentrations

The stack emissions have decreased in recent years and significantly since the 2006 Plant shutdown as shown in Figure 1.17. This emissions reduction are also coupled with an issuing, in the same period, of a revised APPA registration certificate for the East Acid Plant which set stricter limits thus requiring an enhancement of emission reduction measures. The implementation of SO_2 emissions reduction measures discussed in Section 1.7, have by and large, resulted to an overall important reduction in SO_2 emissions from the East Acid Plant as indicated in Figure 1.17. Fugitive emissions which continue to be a challenge due to the corrosive nature of the activity also reduced noticeably indicating positive effect of the air pollution abatement measures implemented. However, when compared to the stack emissions, fugitive emissions have since 2006 reduced in a low order of magnitude. The sulphur imbalance comprises of the fugitive emissions i.e. unaccounted for emissions and the imbalance of the overall mass balance. It is therefore difficult, at this stage, to determine accurately the ratio of fugitive emissions to the sulphur imbalance. The sulphur imbalance fluctuation or variation as observed in Figure 1.17 is due to the currently addressed sulphur accounting problems experienced at the East Acid Plant.

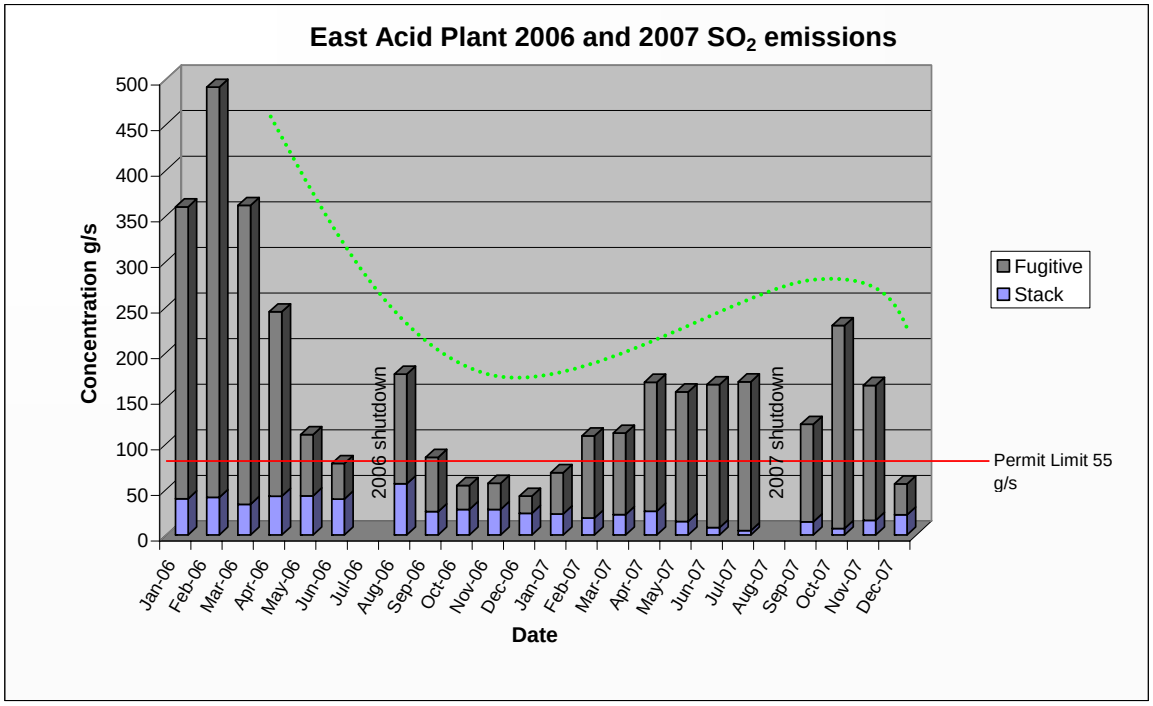

Figure 1.17: East Acid Plant 2006 and 2007 sulphur dioxide emissions derived from the mass balance. The plant shutdowns occurred in July 2006 and August 2007 as indicated by the (information) gaps in the graph

A reduction in stack and fugitive emissions following the implementation of air pollution control measures has not only reduced the Acid Plant SO_2 emissions but has contributed to a decline in concentration levels of ambient SO_2 emissions as indicated in Figure 1.18. The 2007 stack and monitored SO_2 emissions follow a similar trend showing a fairly good relationship and the influence of both emitted and monitored SO_2 emissions. In contrast the sulphur imbalance (or fugitive emissions) shows a significant increase when compared to the stack and ambient SO_2 emissions (Figure 1.19). Fugitive emissions are slightly in line with the ambient conditions though sulphur imbalance statistics are staggeringly high. The high numbers may be due to the problems encountered with sulphur accounting as mentioned previously. Moreover, fugitive emissions from the acid plant may not perpetually be monitored by the ambient stations as it is upwind of the East Acid Plant. Fugitive emissions are monitored at night when the wind is blowing at the direction of the ambient station and when inversion layer is at its lowest (nocturnal conditions) coupled by dominating stable atmospheric conditions. Air pollution rose

(Figure 1.20) for the study period clearly shows the influence of the East Acid Plant on monitored SO_2 concentrations.

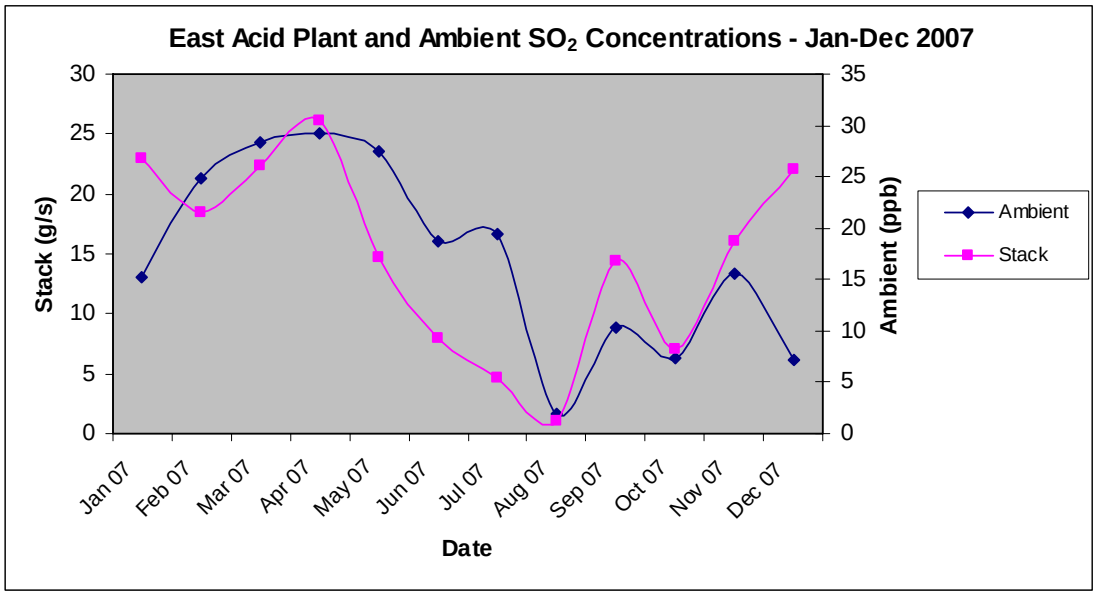

Figure 1.18: AngloGold Ashanti's East Acid Plant (stack) mass balance and monitored ambient SO_2 concentrations for 2007

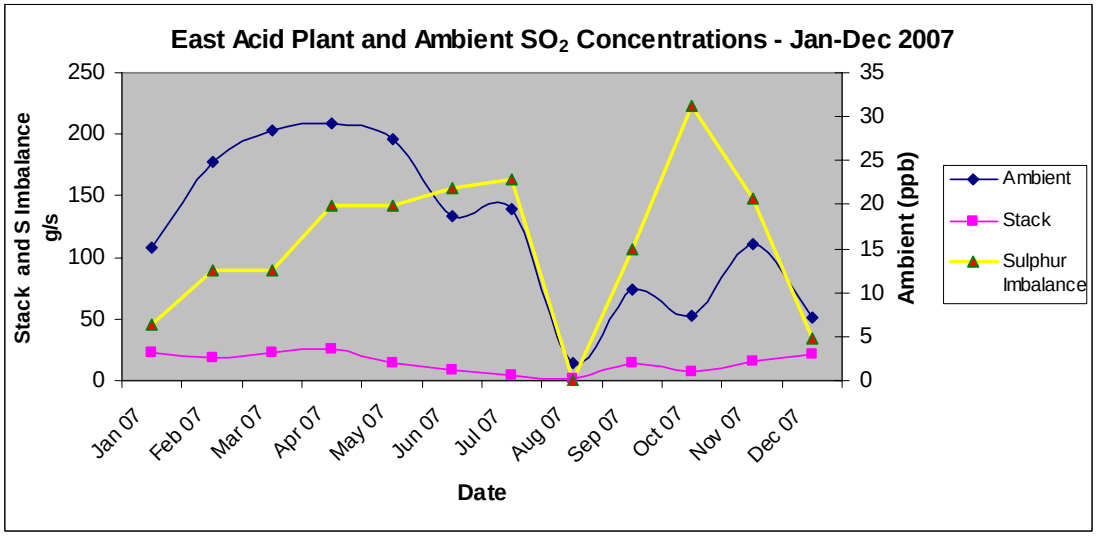

Figure 1.19: AngloGold Ashanti's East Acid Plant (stack and fugitive) mass balance and monitored ambient SO_2 concentrations for 2007

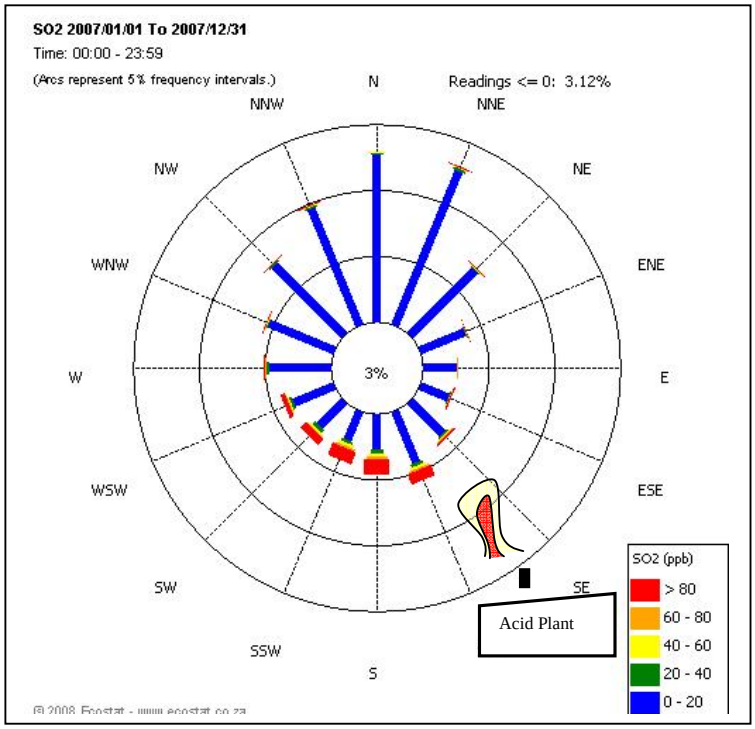

Figure 1.20: Mashie monitoring station SO_2 pollution rose for 2007. The East Acid Plant is located south-east of the ambient station as indicated by the building (stack) replica

1.9. Air quality legislation in South Africa

Air quality management in South Africa has long been governed by the now defunct APPA as amended under various government departments and recently by the national Department of Environmental Affairs and Tourism (DEAT). The APPA regulated the control of noxious and offensive gases emitted by industrial processes, the control of smoke and wind borne dust pollution, and emissions from diesel vehicles. The implementation of the APPA was centralised and charged to the national Chief Air Pollution Control Officers (CAPCO's); however, the new Air Quality Act represents a shift from national air pollution control to decentralised air quality management through a receiving environment. This implies an active participation or involvement of local authority in air quality management (Buthelezi, 2007). Table 1.3 summarises the shortcomings of the APPA and the improvement/changes brought by the new AQA.

Table 1.3: Comparison between Atmospheric Pollution Prevention Act, 1965 and National Environmental Management: Air Quality Act, 2004 (DEAT, n.d.)

APPA, 1965	NEM: Air Quality Act, 2004
• Focus on controls which are: ▪ Source-based rather than receptor-based ▪ End-of-pipe rather than preventative ▪ Command-and-control (little provision for market based controls, voluntary measures, etc) • No meaningful quantitative assessment of ambient air quality • Little to no public participation and access to information	• Shift to the receiving environment approach • Decentralisation of responsibilities • Baseline air quality characterisation • Range of emission reduction measures • All sources to be addressed • Standardisation of monitoring, reporting, QA/QC, etc • Public participation and access to information

A shift from national air pollution control to decentralised air quality management through an effect based approach is the main characteristic of the new air quality legislation. This effects based approach requires the setting of stringent ambient air quality standards. The ambient standards define satisfactory air quality to ensure human health and welfare, the protection of the natural and built environment, and finally the prevention of significant decline in the quality of air. Multiple levels of standards provide the basis for both continued improvements in air quality and for long term planning in air quality management. Although maximum levels of ambient concentrations must be set at a national level, more stringent ambient standards may be implemented by the provincial and local authorities (Liebenberg-Enslin and Petzer, 2005; Buthelezi, 2007).

The current South African standards considered to be outdated were revised in June 2006 (published as Notice 528, Government Gazette No. 28899). The proposed standards (Table 1.4) which are part of Section 9 of the AQA include PM10 (i.e. particulates with an aerodynamic diameter of less than 10 micron), **sulphur dioxide (SO_2)**, oxides of

nitrogen (NOx), ozone (O_3), lead (Pb), carbon monoxide (CO) and benzene (DEAT, 2006; Liebenberg-Enslin et al., 2007).

Table 1.4: Proposed South African ambient air quality standards for common pollutants (Liebenberg-Enslin and Petzer, 2005)

Substance	10-minute maximum	1-hour maximum	8-hour maximum	24-hour maximum	Annual average
Sulphur Dioxide (SO_2)	500 $\mu g.m^{-3}$	350 $\mu g.m^{-3}$	-	125 $\mu g.m^{-3}$	50 $\mu g.m^{-3}$
Nitrogen Dioxide (NO_2)	-	200 $\mu g.m^{-3}$	-	-	40 $\mu g.m^{-3}$
Carbon Monoxide (CO)	-	30 $\mu g.m^{-3}$	10 $\mu g.m^{-3}$	-	-
Particulate Matter (PM_{10})	-	-	-	75 $\mu g.m^{-3}$	40 $\mu g.m^{-3}$
Ozone (O_3)	-	200 $\mu g.m^{-3}$	120 $\mu g.m^{-3}$	-	-
Lead (Pb)	-	-	-	-	0.5 $\mu g.m^{-3}$
Benzene (C_6H_6)	-	-	-	-	5 $\mu g.m^{-3}$

Note: Measurement of the amount or concentration of each of the substances shall be standardised at standard temperature (25°C) and pressure (101.3 kPa)

According to the AQA, a National Framework must be developed within two years of the enactment of air quality legislation. The National Framework must provide mechanisms, systems and procedures to attain compliance with the ambient air quality standards and emissions control from point and non-point sources. In addition, national norms and standards need to be set for air quality monitoring, management planning, information management, etc (Liebenberg-Enslin et al., 2007). A 1st Generation National Framework has already been published and will be revised once the DEAT's contributing air quality projects are finalised to produce a 2nd Generation National Framework (DEAT, 2007).

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Regional air quality, the pollutants and meteorological conditions influencing air quality have been discussed. Sources of sulphur dioxide emissions and those specific to AngloGold Ashanti's Vaal River operations have been highlighted and the research goals outlined. Previous modelling study, stack emissions, monitored ambient air quality data is presented. Data and methods will be discussed in chapter two.

CHAPTER 2 : DATA AND METHODS

Chapter two highlights air quality and meteorological monitoring at AGAs Vaal River operations. The model and methods including input data used in this research are described. The meteorology of the study area is discussed.

2.1 Air quality and meteorological monitoring at AngloGold Ashanti's Vaal River Operations

AngloGold Ashanti's Vaal River Operations began air quality monitoring in July 2005 following the identification of non-compliance areas by Scorgie and Venter in 2004. Revision of the APPA registration certificates by the then CAPCO for the East Acid Plant and Vaal River laboratory also necessitated the enhancement of monitoring system and a continuous emission monitoring (CEM) suite was installed on the East Acid Plant stack.

The monitoring network consists of two ambient stations monitoring SO_2 and PM10, situated at Vaal River Mashie golf course and the South Uranium Plant. The monitoring network also includes four (4) meteorological stations including an upper air station at Vaal River (3) and West Wits (1) as well as a dilution probe (CEM) installed at the East Acid Plant stack (Figure 2.1). Meteorological parameters monitored are temperature, wind speed and direction, pressure, rainfall, solar radiation and relative humidity.

The measured ambient air quality results pertain to instantaneous samples drawn from air passing the above fixed stations. All results are reported at standard temperature and pressure; and can either be expressed over 10-minute, 1-hour, 24-hour, monthly or annual averaging periods. The dilution probe consists of a stack-mounted Sample Probe, Control Panel, and an unheated Umbilical Cord which carries a gas sample to an SO_2 analyser (Figure 2.1). Designed to function as a sample conditioning and transport

system, the EPM dilution probe filters particulates, reduces moisture content to levels below the dew point, dilutes the sample to more accurately measured concentrations, and transports it under positive pressure to the analyser (Piketh and Rautenbach, 2004). The SO_2 data from the analyser is then used by the East Acid Plant personnel to effectively control the plant's SO_2 emissions and also to populate the operational mass balance model.

Figure 2.1: The dilution probe that consists of a stack-mounted EPM Sample Probe (A) and SO_2 data analyser (B)

Figure 2.2: AngloGold Ashanti Vaal River air quality monitoring network and (other) air pollution sources in the area. Yellow marks indicate the monitoring stations; Green marks and blue text (AVRs) indicate dust fallout buckets and Red marks are some of the additional air pollution sources in the area

2.2 Meteorological conditions in Vaal River for 2007

The Vaal River regional climate is typical of the Highveld with moderately wet, warm summers and cold dry winters associated with significantly low relative humidity and high evaporation rates. The annual average temperature is 14.2 / 17.1 ^{o}C (wet bulb; dry bulb) and a typical temperature and net radiation profile in shown in Figure 2.3. Northerly winds dominate Vaal River's wind structure and there is a greater frequency of westerly winds as portrayed in Figure 2.4. Meteorological data processed from the MM5 model (Figure 2.5) depicts meteorological conditions similar to those monitored at the Vaal River ambient station (Figure 2.4). No significant deviation from this pattern is noted between winter and summer, and the dispersion of pollutants is likely to follow a similar pattern during both seasons. Wind speeds are less than 6 m.s^{-1} for most of the time with calm winds (<1 m.s^{-1}) occurring 30% of the time. Above average winds were experienced as indicated by the number of calms and this may have culminated into mixing in the atmosphere and dispersion of pollutants.

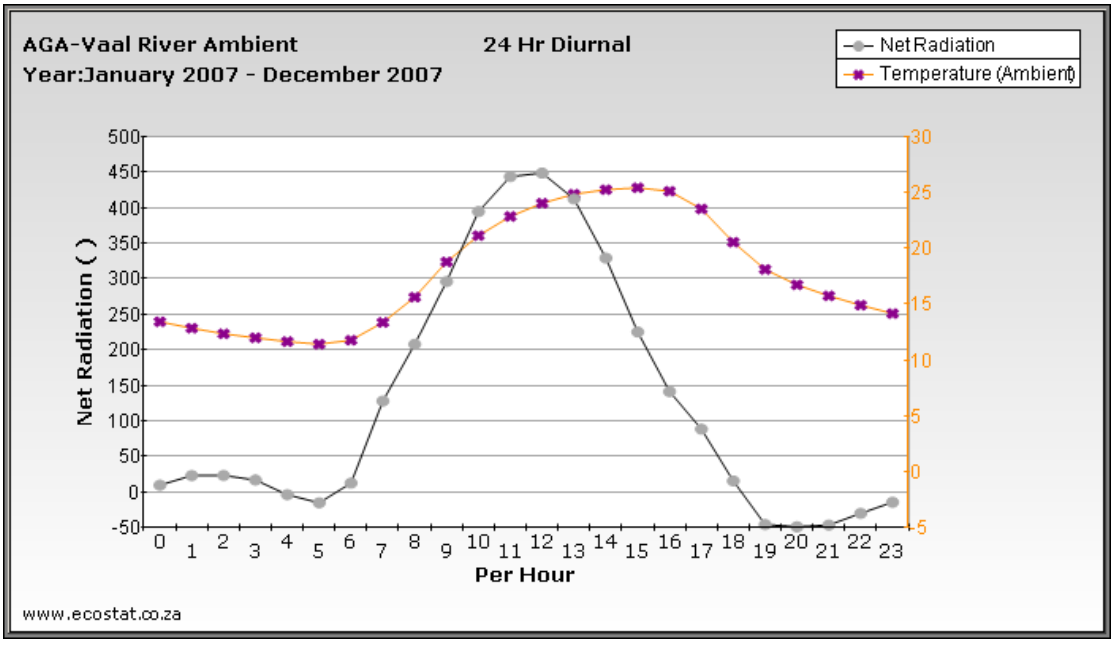

Figure 2.3: Ambient temperature and net radiation profile for January through December 2007

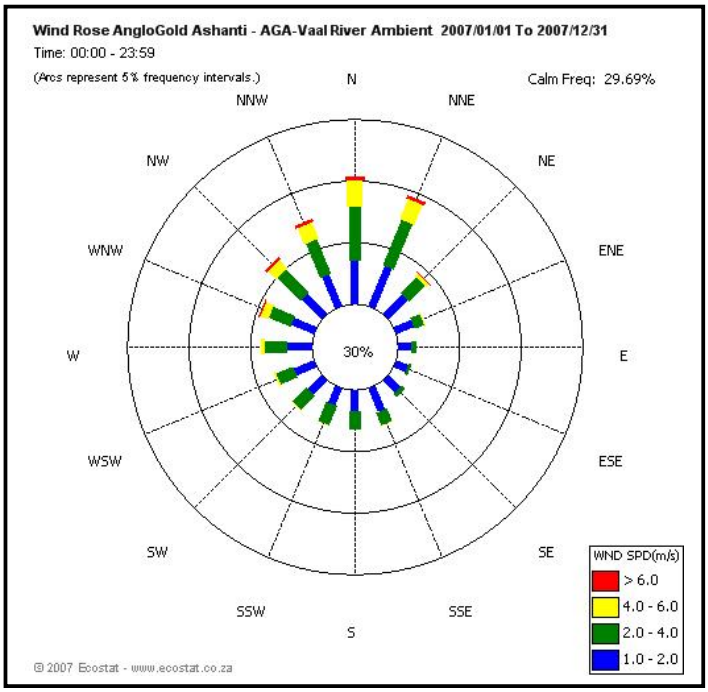

Figure 2.4: Surface wind rose for Vaal River meteorological station, January through December 2007

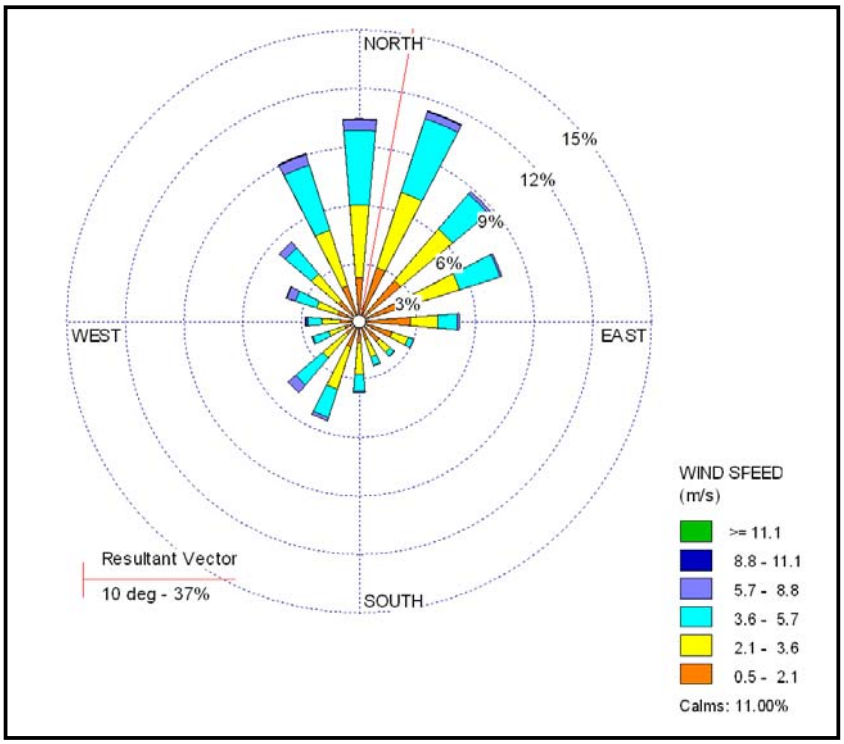

Figure 2.5: MM5 derived wind rose for Vaal River, January through December 2007

2.3 AERMOD dispersion model

2.3.1 Model overview

AERMOD, applied in this study, is a 'near-field' steady-state Gaussian model (Figure 2.7) designed for short range (< 50km) dispersion of air pollutant emissions from stationary industrial sources. This USEPA approved model was developed in 1995, reviewed in 1998 and fully promulgated as a replacement to ISCST3 in December 2006. AERMOD uses boundary-layer similarity theory to define turbulence and dispersion coefficients as a continuum, rather than as a discrete set of stability classes. Variation of turbulence with height allows a better treatment of dispersion from different release heights. Also, the dispersion coefficients for unstable conditions are non-Gaussian, to represent the high concentrations that can be observed close to a stack under convective conditions (New Zealand Ministry for the Environment, 2004; USEPA, 2004).

The AERMOD modelling system consists of two pre-processors i.e. AERMET and AERMAP and the actual dispersion model. A meteorological data pre-processor (AERMET) provides AERMOD with the meteorological information it needs to characterize the planetary boundary layer (PBL). It accepts surface meteorological data, upper air soundings, and optionally, data from on-site instrument towers. AERMET then calculates atmospheric parameters needed by the dispersion model, such as atmospheric turbulence characteristics, mixing heights, friction velocity, Monin-Obukhov length and surface heat flux. A terrain pre-processor (AERMAP) provides a physical relationship between terrain features and the behaviour of air pollution plumes. It generates location and height data for each receptor location and provides information that allows the dispersion model to simulate the effects of air flowing over hills or splitting to flow around hills (USEPA, 2004, Brode, 2006; Prater and Midgley, 2006). An updated AERMAP version 06341 was recompiled in 2007 to accept three characters instead of two for UTM zone parameter (e.g. UTM-22) (Lakes Environmental Software, 2007). This recompiled version, applied in this study, is recommended to be used for projects located in the southern Hemisphere because three characters are required as input in the

UTM zone parameter. AERMOD in addition includes PRIME (Plume Rise Model Enhancements) which is an algorithm for modelling the effects of downwash created by the pollution plume flowing over nearby buildings (Schulman et al., 2000). Figure 2.6 shows the flow and processing of information in AERMOD.

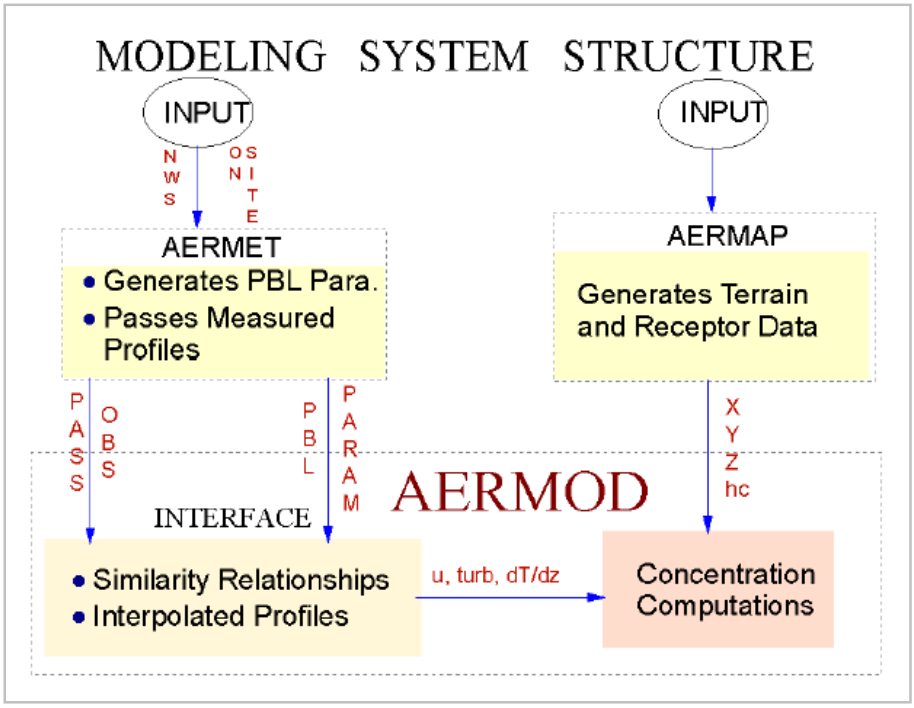

Figure 2.6: Data flow in the AERMOD modelling system (USEPA, 2004)

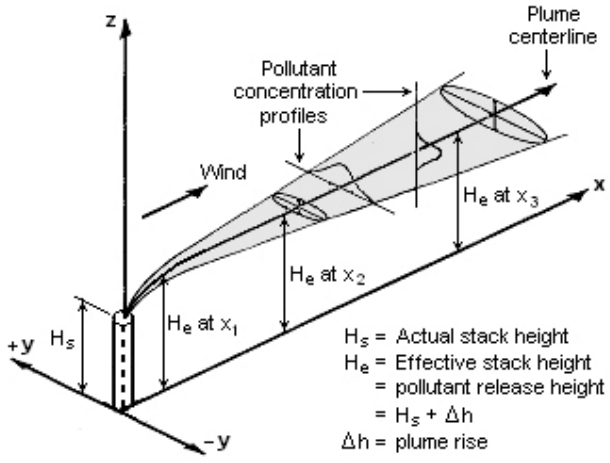

Figure 2.7: Gaussian distribution of concentrations in the horizontal and vertical directions from an elevated point source (Wayson et al., 2000)

2.3.2 Planetary boundary layer (PBL) statistics correction

Constructing realistic planet planetary boundary layer (PBL) similarity profiles and adequately characterizing the dispersive capacity of the atmosphere is critical in order to ensure that air dispersion models account for correct atmospheric processes in simulations which are important for pollutant dispersion as discussed in Section 1.5.2. A crucial finding was made by the University of Witwatersrand's Climatology Research Group (particularly Roelof Burger) during this study. This finding entails a correction to the AERMET's boundary layer algorithm, AERMOD's meteorology pre-processor. AERMET was hard-coded to calculate boundary layer parameters using the western-hemispheric sounding just before sunrise. A simple correction to the AERMET code to convert sounding times to local time and then look for the morning sounding has a dramatic impact on the accuracy of boundary layer calculations. AERMET's pre-processed surface and profile meteorological data were corrected following the calculation of the mixing height.

An uncorrected boundary layer height (Figure 2.8) shows convective planetary boundary layer (CPBL) starting at a notional 2000m from 6am and steadily increasing with a rise in solar radiation. A corrected boundary layer height (Figure 2.9) shows convective boundary layer starting at about 100m from 6am as expected and steadily increasing with a rise in solar radiation. The changed CPBL statistics are more realistic and indicative of the typical meteorological conditions experienced during daytime. Mechanical planetary boundary layer (MPBL) was not changed as it was unnecessary.

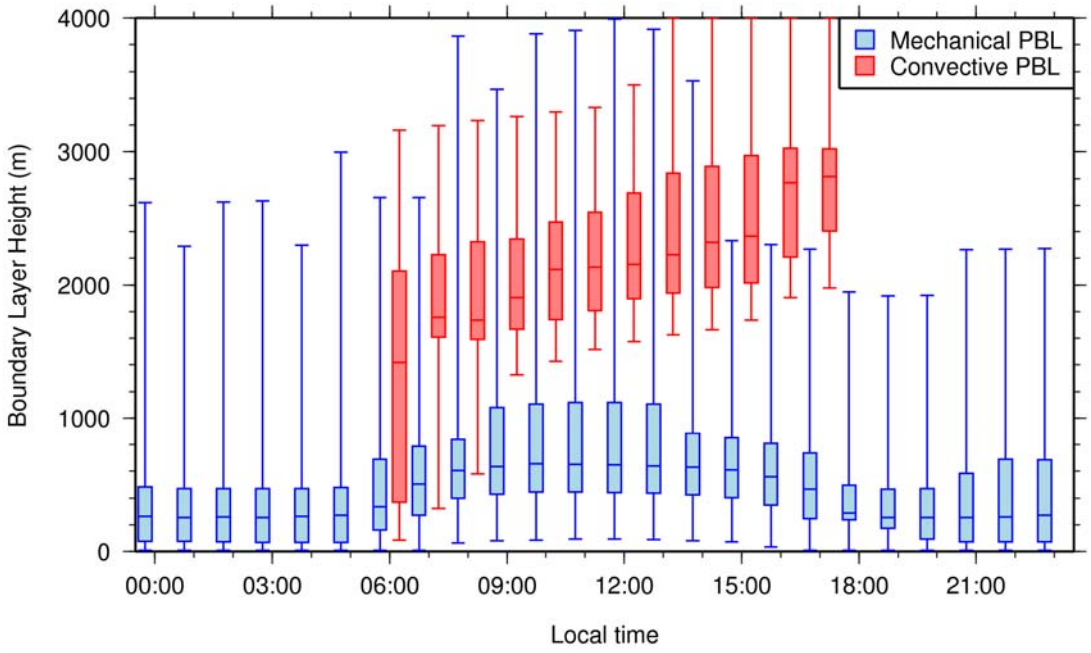

Figure 2.8: Unchanged AERMET boundary layer statistics (Burger, 2007)

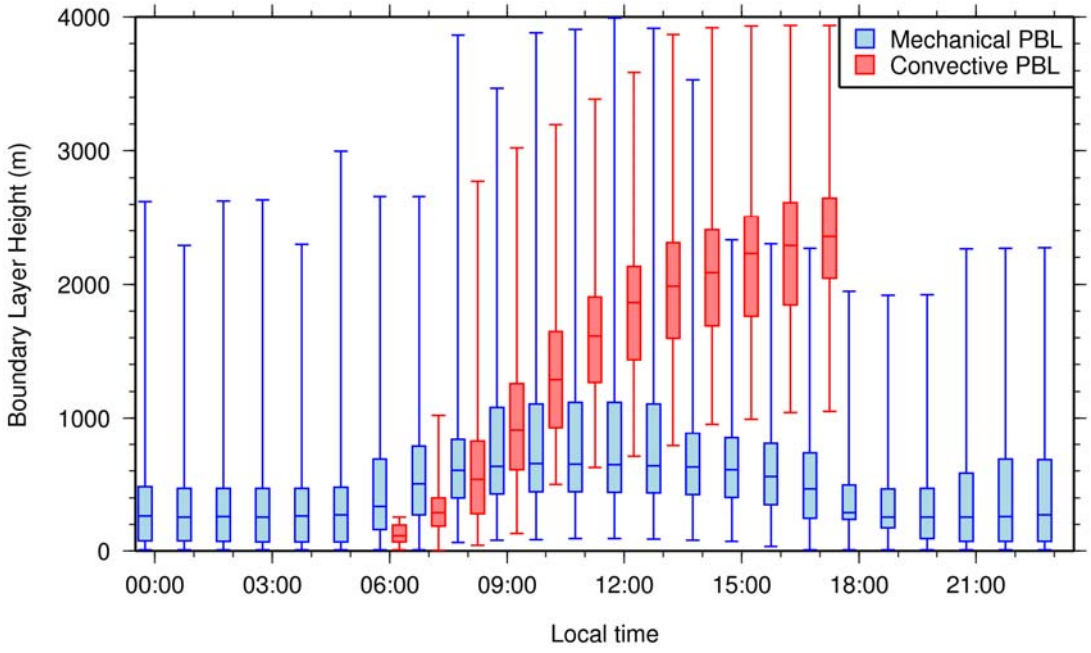

Figure 2.9: Changed (corrected) AERMET boundary layer statistics (Burger, 2007)

2.3.3 Model input data

2.3.2.1 Modelling domain and grid resolution

Total modelling domain coverage of 20km by 20km, with a grid resolution of 1km was used in the simulations to, amongst other reasons, reduce the model noise error. This modelling domain was selected to include any regions of sensitive or important receptors such as the nearby Vaal River village and Umuzimuhle mine residential areas and the few farmers in the area. Uniform Cartesian grid receptor type was selected in AERMOD to specify receptor location for this particular model runs.

2.3.2.2 Geophysical data

Terrain and land-use data applied include surface elevations and land-use categories. This data was sourced via Lakes Environmental courtesy of National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS). Terrain data used has a ~90m, 3 arc-second resolution based on WGS84 datum. Since no major topographical features are located within the immediate vicinity of the study area, a flat terrain option was used. Therefore the model's performance to handle complex terrain and its influence on the results will not be discussed in this report.

2.3.2.3 Meteorology

Surface and profile meteorological data for 2007 was processed using Mesoscale Model 5 (alias MM5), a three dimensional numerical meteorological model that has proven useful for air quality applications. MM5 is a limited area, terrain-following (sigma-coordinate), prognostic meteorological model. It solves the full suite of non-hydrostatic prognostic primitive equations for the three-dimensional wind, temperature, water (in all phases), and pressure fields. It can be run with multiple one-or two way nested grids to

resolve a range of atmospheric processes and circulations on spatial scales from one to several thousands of kilometres. Currently, MM5 uses seven planetary boundary layer (PBL) parameterizations schemes to represent turbulent fluxes of heat, moisture, and momentum (Chang et al., 2000; Sarma, 2008).

MM5 model was purposely implemented for a pre-defined domain covering an area large enough to account for the air flow during the 2003-2007 simulation periods. Only the 2007 processed meteorological data was used in this study and the rest of the data applied to other AGA's projects. A 12 km x 12km grid cell dimension was applied. However, it is important to acknowledge that such a coarse scale compared to a fine model domain may result in improper resolution of actual atmospheric differences thus resulting in ineffective predictions. MM5 output data was processed via AERMET in preparation for use in AERMOD. Three meteorological files were created and input into AERMOD.

As a rule, site-specific data is always preferred when developing a meteorological data profile for a specific source. However, sometimes this is not possible as it is the case with this study. The MM5 model data was used due to inadequate meteorological data availability in the study area, particularly the profile data. The recently commissioned AngloGold Ashanti's upper air station is not fully operational and the closest upper air stations i.e. Irene and O.R. Tambo International Airport are in excess of 150km from the study area. These meteorological stations are therefore largely non-representative of source locations. Application of MM5 output data into AERMET/AERMOD enabled the location of surface and upper air data in the same grid cell, thus improving the models accuracy and enhancing dispersion model valuation.

2.3.2.4 Mass balance calculated SO_2 emissions

Mass balance model, as outlined in Appendix 1, was used to quantify the acid plant's stack SO_2 emissions. In general, mass balance refers to the quantification of total materials into and out of a process, with the difference between inputs and outputs being accounted for in terms of releases (emissions) to the environment, or as part of the plant waste. It is essential to recognise that the estimates derived using mass balances are only as good as the values used in performing the calculations. For example, small errors in data or calculation parameters (e.g. pressure, temperature, stream concentration, flow, control efficiencies, etc) can result in large errors in the final emission estimations. Additionally, if sampling of input or output materials is conducted, failure to use representative samples will also contribute to the uncertainty of the mass balance and modelling result.

At AngloGold Ashanti, the mass balance procedure used to quantify the East Acid Plant's SO_2 emission rate is formulated using Fe, Si, S, O, H, and N sample from the feed stock. These parameters indicate the amount of sulphur in the feed stream, usually around 30%. Calcine tonnage and calcine water tonnage is calculated with a Fe and Si balance and fugitive SO_2 (also defined as the sulphur imbalance) is calculated through the overall balance of sulphur. SO_2 emissions data from the stack analyser is integrated into the mass balance model to calculate the amount of sulphur emitted in the stack and also to determine the proportion of stack emissions to the fugitive emissions. Mass balance SO_2 emission rates (factors) are used in this study together with the monitored ambient air quality data for 2007.

Annual average and variable SO_2 emission factors by month together with source characteristics such as the stack height, stack diameter, gas exit velocity and gas exit temperature were input into the model. POSTFILES post-processing calculations involved 1-hour, 24-hour and annual averaging periods for 2007.

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Chapter two gives an outline of air quality monitoring at AGAs Vaal River operations. An overview of AERMOD, methods and input data has been given. The meteorological conditions in Vaal River have been discussed. Dispersion modelling results are discussed in chapter three

CHAPTER 3 : RESULTS AND DISCUSSION

Chapter three outlines the AERMOD modelling results for various sources. Emissions from the East Acid Plant are particularly discussed in detail. Ambient data is used to verify modelling results and AERMOD's suitability to model emissions is discussed.

3.1 Modelling results (concentration contours analysis)

Various modelling scenarios were undertaken using 2007 mass balance emission rate for stack emissions at the East Acid Plant. Mass balance data for 2007 fugitive emissions was not used in this study due to gaps in the information and other prohibitive reasons highlighted in the previous sections of this report. Emission factors (EFs) were therefore applied to model significant (volume) fugitive sources at the East Acid Plant. Point and volume sources at Great Noligwa No. 8 Gold Plant and the South Uranium Plant were modelled using emission factors as there is no mass balance data and these processes are currently not required to be registered with the CAPCO. These EFs were developed during the AGA air quality studies undertaken by Airshed Planning Professionals and Environmental Science Services Africa (ESSC) in 2003/4. The East Acid Plant 2007 stack SO_2 emissions were modelled from January through July (prior plant shutdown) and September through December (post plant shutdown). This was aimed at determining improvement (or lack thereof) in controlling emissions following the implementation of air pollution abatement measures.

In order to assess the impact on air quality in and around the East Acid Plant and other identified AGA sources, 1-hour, 24-hour and annual average SO_2 concentrations are presented in the form of concentration contours. This is aimed at determining the spatial distribution of SO_2 over the modelled area (Figures 3.1 through 3.4) and to facilitate comparison with the national ambient air quality standards. The East Acid Plant contour plots for variable emission rates by month are presented only for 1-hour and 24-hour averaging periods for reasons stated above. Contour plots reflecting hourly and daily

averaging periods contain only the highest predicted ground level concentrations for that averaging period, over the entire period for which simulations were undertaken. It is therefore possible that even though a high daily concentration is predicted to occur at certain locations, that this may only be true for one day during the entire period. The modelled concentrations are compared to the South African ambient air quality standards in Table 3.1.

3.1.1 Modelled concentrations from the stack and volumes sources

The *maximum one-hour average* SO_2 concentration field predicted for the stack and volume sources combined appears to be more realistic (Figure 3.1) as high concentrations exceed 1000 $\mu g.m^{-3}$due to the high level emissions from all the combined sources. The model predicts the highest concentrations from the East Acid Plant (EAP) with 1051 $\mu g.m^{-3}$ predicted to occur downwind and just outside the boundary of the plant, about 300m south east of the plant.

The South Uranium Plant and Great Noligwa No. 8 Gold Plant are minor contributors to predicted emissions concentrations. Fugitive emissions and enabling meteorological conditions are possible contributors to the creation of the zone of higher concentrations closer to the source i.e. EAP. The one-hour average standard of 350 $\mu g.m^{-3}$ (Table 3.1) is exceeded in all directions within 2.5km of the EAP. These higher concentrations and exceedances encompass the residents of the Vaal River Village, <1km north-west of the EAP and Umuzimuhle Township, 1.8km south-west of the EAP.

The *maximum 24-hour average* SO_2 concentrations of 284 $\mu g.m^{-3}$ is predicted <300m north-east of the East Acid Plant (Figure 3.1). The zone of higher concentrations closer to the source is probably the result of fugitive emissions and highly unstable conditions, while the high concentration zone further from the EAP is probably due to the plume dispersing to the elevated ground more gradually under less unstable or neutral

conditions. The 24-hour average standard of 125 μg.m^{-3} is exceeded in all directions within 600m of the EAP. The Mashie ambient air quality monitoring station falls within the zone of maximum influence

The *maximum annual average* SO_2 concentration of 25 μg.m^{-3} is predicted to occur in close proximity of the EAP indicating this source as a major contributor to the high SO_2 concentrations (Figure 3.1). Other sources i.e. Great Noligwa Gold Plant and the South Uranium Plant situated south-east of the EAP contribute minimally to predicted emissions. The predicted annual concentrations from the above sources comply with the annual average standard of 50 μg.m^{-3} (Table 3.1). The plume strike (Figure 3.1) mimics the prevailing wind direction of the area depicted in the annual wind roses (Figures 2.4 and 2.5).

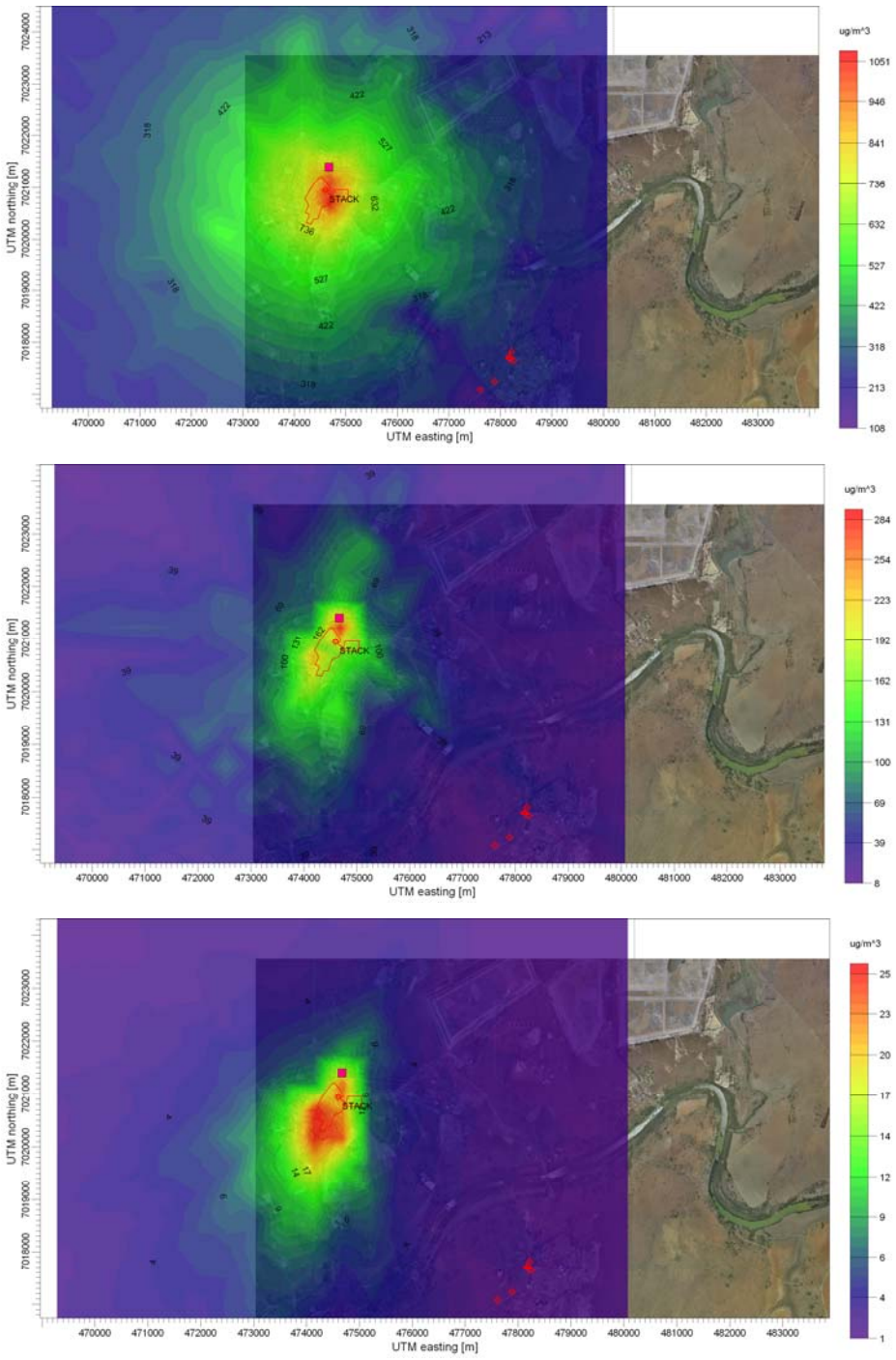

Figure 3.1: Maximum 1-hour (top), 24-hour (middle) and Annual (bottom) average concentrations ($\mu g.m^{-3}$) due to the East Acid Plant (red boundary), Great Noligwa Gold Plant and the South Uranium Plant (red asterisks in SW). Red square represents the Mashie ambient air quality monitoring station

3.1.2 Modelled East Acid Plant stack concentrations (January-December 2007)

The *maximum one-hour, 24-hour and annual average* SO_2 concentration fields predicted for the East Acid Plant (EAP) stack (Figure 3.2) comply with the South African standards for these averaging periods as indicated in Table 3.1. Higher concentrations in the selected averaging periods occur in a zone between 1.5 km north of the EAP and 7km south-east of the EAP, both uninhabited (open) areas. The plume strikes for both 24-hour and annual averages mimic the prevailing wind direction of the Vaal River area.

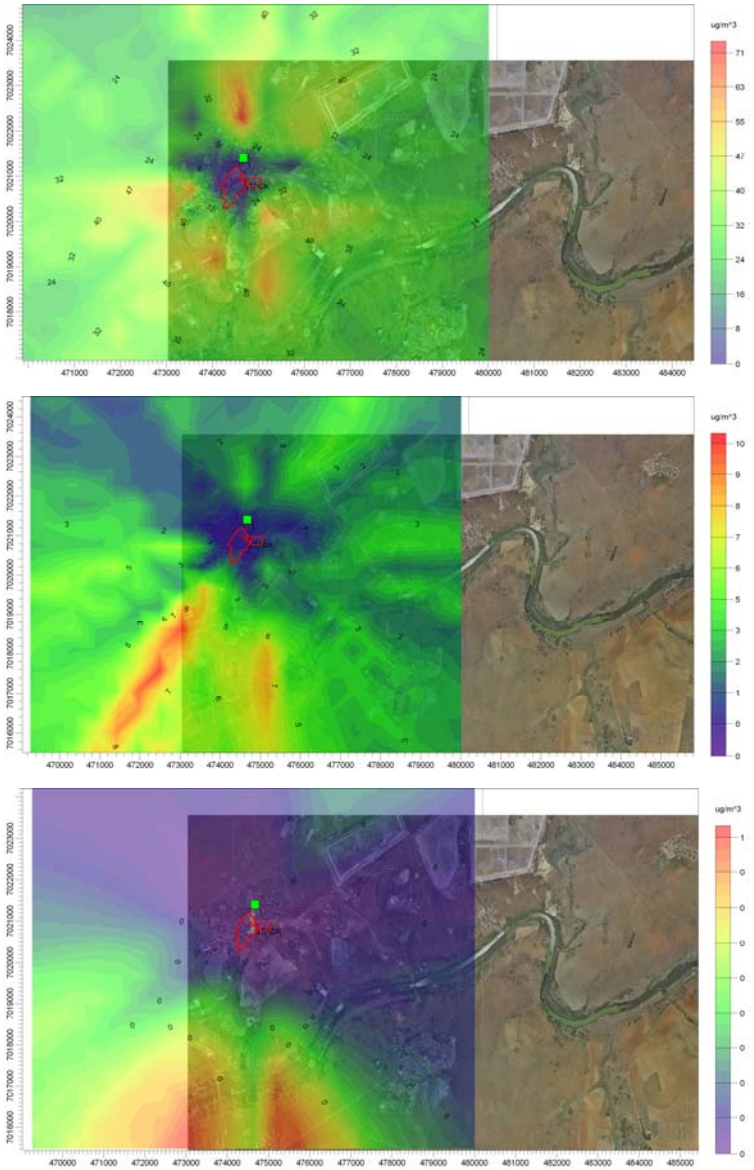

Figure 3.2: Maximum 1-hour (top), 24-hour (middle) and Annual (bottom) average concentrations ($\mu g.m^{-3}$) for the East Acid Plant stack (2007)

3.1.3 Modelled stack concentrations prior the East Acid Plant shutdown (January-July 2007)

The *maximum one-hour average* SO_2 concentration field predicted for the stack (excluding fugitive emissions) is 111 $\mu g.m^{-3}$ and occurs south-east of the EAP (Figure 3.3). The higher concentrations occur in a southerly direction of the EAP between 1.6km and 2.5km. These higher concentration zones encompass the residents of the Umuzimuhle Township and some of the open (veld) areas. The SO_2 one-hour average air quality standard of 350 $\mu g.m^{-3}$ is complied with (Table 3.1).

The *maximum 24-hour average* SO_2 concentration of 11 $\mu g.m^{-3}$ is predicted 5.7 km south-west of the Acid Plant (Figure 3.3). The high concentration zone further from the EAP is probably due to the plume dispersing to the elevated ground more gradually under less unstable or neutral conditions. Residential areas adjacent to the EAP i.e. Umuzimuhle and Vaal River village are exposed to the predicted minimal SO_2 concentrations. The SO_2 24-hour average standard of 125 $\mu g.m^{-3}$ is complied with as indicated in Table 3.1.

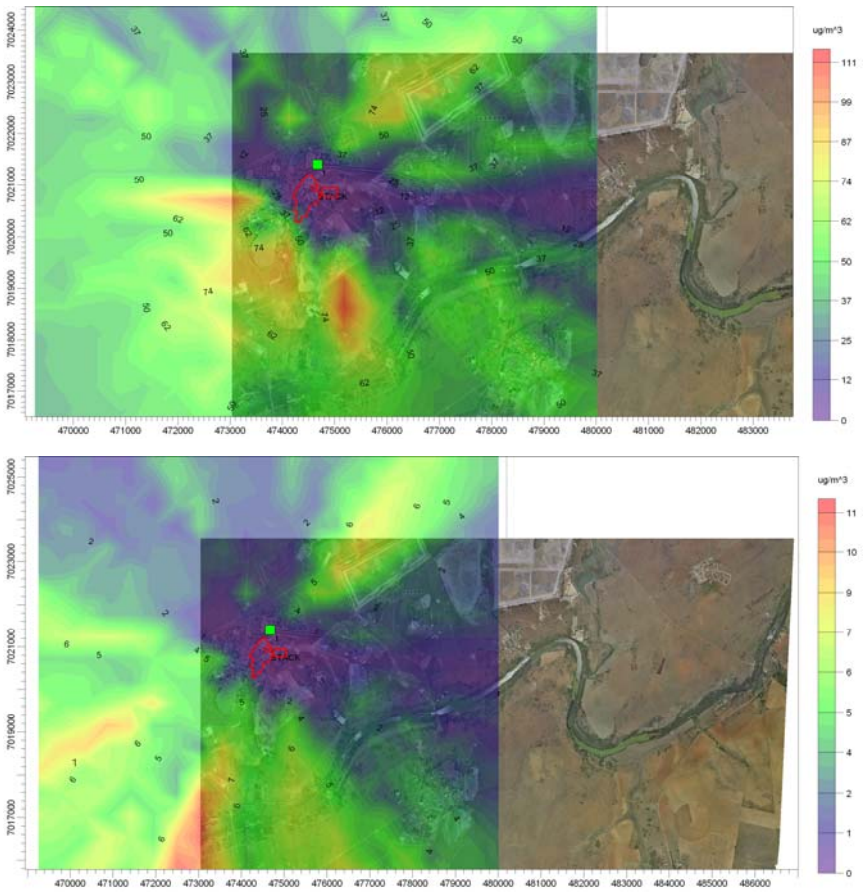

Figure 3.3: Maximum 1-hour (top) and 24-hour (bottom) average concentrations ($\mu g.m^3$) due to the East Acid Plant (red boundary) prior plant shutdown

3.1.4 Modelled stack concentrations post the East Acid Plant shutdown (September-December 2007)

The *maximum one-hour average* SO_2 concentration field predicted for the stack (excluding fugitive emissions) is 48 $\mu g.m^{-3}$ (111 $\mu g.m^{-3}$ prior shutdown) and occurs 2km north-east of the EAP (Figure 3.4). The higher concentrations occur in various directions of the EAP and encompass residential and some of the open (veld) areas. The predicted concentrations are lower compared to the concentrations prior the EAP maintenance shutdown. This may be attributed to the effectiveness of emission reduction measures

implemented during the plant shutdown. The SO_2 one-hour average standard 350 $\mu g.m^{-3}$ is complied with (Table 3.1).

The *maximum 24-hour average* SO_2 concentrations is 9 $\mu g.m^{-3}$ (11 $\mu g.m^{-3}$ prior shutdown) and is predicted to occur >3 km south-west of the Acid Plant (Figure 3.4). The high concentration zone further from the EAP is probably due to the plume dispersing to the elevated ground more gradually under less unstable or neutral conditions. Residential areas adjacent to the EAP i.e. Umuzimuhle, Vaal River village and few farmers are exposed to the predicted minimal SO_2 concentrations. The SO_2 24-hour average standard 125 $\mu g.m^{-3}$ is complied with (Table 3.1).

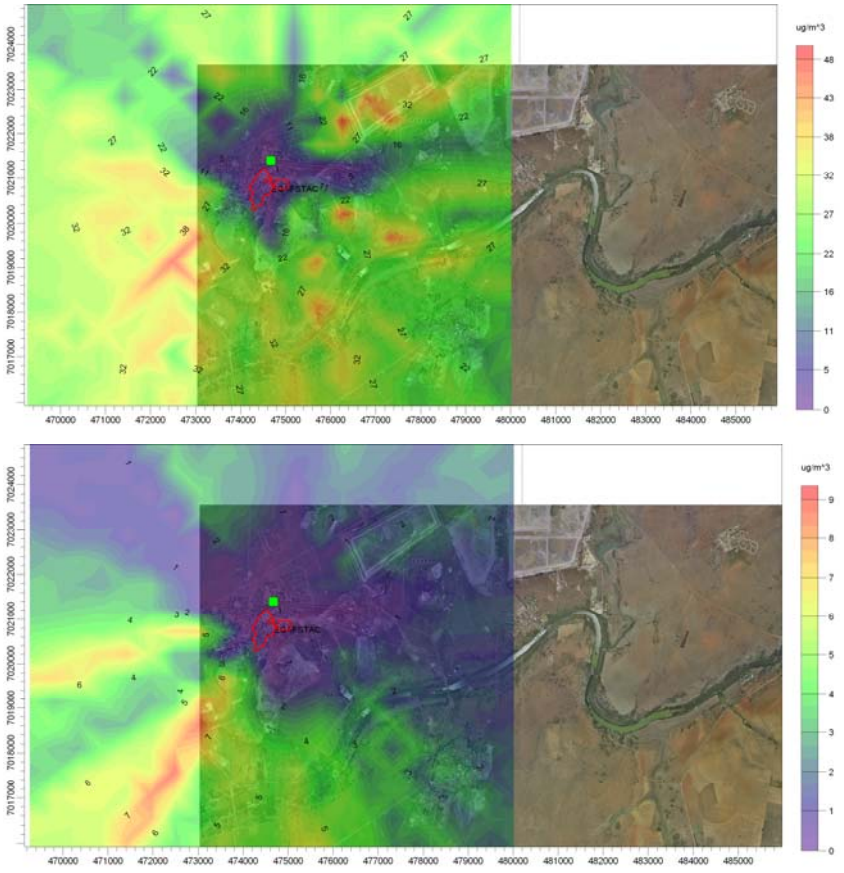

Figure 3.4: Maximum 1-hour (top) and 24-hour (bottom) average concentrations ($\mu g.m^{-3}$) due to the East Acid Plant (red boundary) post plant shutdown

Table 3.1: Comparison of modelled SO_2 concentrations with the South African ambient air quality guidelines

	Average ($\mu g.m^{-3}$)	1-hour maxi-mum guideline ($\mu g.m^{-3}$)	24-hour maximum guideline ($\mu g.m^{-3}$)	Annual maximum guideline ($\mu g.m^{-3}$)
Modelled stack and volume concentrations				
Max 1-hour	1051	350	-	-
Max 24-hour	284	-	125	-
Max annual	25	-	-	50
Modelled Acid Plant stack concentrations (January-December 2007)				
Max 1-hour	71	350	-	-
Max 24-hour	10	-	125	-
Max annual	1	-	-	50
Modelled stack concentrations prior the Acid Plant shutdown (January-July 2007)				
Max 1-hour	111	350	-	-
Max 24-hour	11	-	125	-
Modelled stack concentrations post the Acid Plant shutdown (August-December 2007)				
Max 1-hour	48	350	-	-
Max 24-hour	9	-	125	-

3.2 Model performance assessment

In the verification of 2007 dispersion model results, predicted concentrations arising due to the emissions from AGA sources were compared to measured concentrations at the Mashie ambient monitoring station for the same period. Modelled concentrations are based on a constant source emission rate and are thus influenced by the prevailing meteorological conditions for each hour. The model generally over-predicts along the

plume centreline in the region of maximum impact and elsewhere. Modelled and measured average and maximum SO_2 concentrations at the monitoring site are given in Table 3.2.

Table 3.2: Comparison of measured and modelled SO_2 concentrations at the Mashie ambient air quality monitoring station adjacent the East Acid Plant

	1-hour maximum ($\mu g.m^{-3}$)	**Number of 1-hr exceedances**	**24-hour maximum ($\mu g.m^{-3}$)**	**Number of 24-hour exceedances**
Ambient monitoring station concentrations	2015	4	576	26
AERMOD – stack and volume concentrations	1051	>50	284	8
AERMOD – stack **only** concentrations	71	0	10	0

AERMOD significantly under-predicts the 1-hour and 24-hour maximum average concentrations for the stack (only) and the stack and volume emissions combined (Table 3.2) at the Mashie ambient monitoring station (400m north of the East Acid Plant). This could be as a result of the fact that the monitoring station is located upwind of the East Acid Plant and therefore maximum zones of impact differ between monitored and modelled data. Moreover, background SO_2 concentrations from various local sources such as the medical waste incinerator (north-west of the EAP), were not taken into account during this study.

The predicted stack and volume source concentrations are acceptably high compared to the predicted emissions for the stack only (Table 3.2). A high number of 1-hour exceedances of 350 $\mu g.m^{-3}$ air quality limit are predicted by the model compared to the few exceedances measured at the ambient monitoring station. The model predicts less 24-hour exceedances of 125 $\mu g.m^{-3}$ air quality compared to the higher measured exceedances. No exceedances for the stack only concentrations are predicted by the model whereas a number of exceedances are measured at the ambient air quality monitoring station (Table 3.2). AERMOD predicts significantly higher SO_2 concentrations for lighter wind speeds closer to the stack. This is expected, since the downwash algorithms are better for refined Gaussian models than in puff models closer to the source (Ross *et al*., 2006).

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Chapter three described the AERMOD output of predicted concentrations from the stack (only) and stack and volume sources (combined). Comparison between modelled and monitored concentrations was discussed and model performance evaluated. The summary and conclusions are provided in chapter four

CHAPTER 4 : SUMMARY AND CONCLUSIONS

This chapter concludes the main findings of this study, indicating the suitability of AERMOD to model SO_2 concentrations from the AngloGold Ashanti's Vaal River operations, particularly the East Acid Plant

The primary objective of this study was to determine the impacts from implementing air pollution abatement measures at AngloGold Ashanti's East Acid Plant, whilst establishing the relationship between the acid plant emissions and monitored ambient air quality data. This was achieved through dispersion modelling of a major SO_2 emission source; however emission factors were used to incorporate minor sources in the modelling scenarios. The following conclusions are based on the three SO_2 pollution sources that were identified at AngloGold Ashanti's Vaal River for modelling, namely, the East Acid Plant, South Uranium Plant and Great Noligwa No. 8 Gold Plant. The East Acid Plant was the focal source for this study and therefore its comprehensive 2007 mass balance SO_2 emissions prior and post plant shutdown were selected for modelling purposes. A steady-state Gaussian model, AERMOD was used to predict SO_2 concentrations in and around the East Acid Plant domain.

As part of this research, calculation errors posed by AERMET were corrected resulting to an improved accuracy by the model to calculate the mixing height. The corrected convective planetary boundary layer (CPBL) similarity profiles were therefore more realistic, representative of typical daytime meteorological conditions and enabled adequate characterisation of the dispersive capacity of the atmosphere. Surface and profile meteorological data was processed using Mesoscale Model 5 (MM5) due to the inadequate meteorological data availability in the area, particularly the profile data. The recently commissioned AGA's upper air station was inoperative and therefore could not provide profile data for use in AERMET. Meteorological data processed from the MM5 model depicted meteorological conditions similar to those monitored at the Vaal River ambient station and this was important to acquire accurate modelling results.

The implementation of air pollution control measures in 2007 resulted to an overall important reduction in sulphur dioxide emissions from the East Acid Plant which signified the influence and/or efficiency of such measures. A 30% reduction in the Acid Plant emissions has further contributed to a decrease in ambient SO_2 concentration levels for the same period. In agreement with the mass balance results and ambient monitoring data, AERMOD modelling results showed a reduction in SO_2 concentration after the Acid Plant shutdown in the third and fourth quarter of 2007. The evident reduction in emissions will reduce exposure of sensitive receptors to elevated levels of SO_2 concentration that are prevalent in the Highveld region (Vaal Reef) which experiences poor atmospheric dispersion potential for a substantial portion of the year.

The East Acid Plant was identified as a significant contributor to SO_2 emissions due to the sulphuric nature of the activity. This finding agreed with the Scorgie and Venter (2004) study which also marked the Acid Plants as important sources of sulphur dioxide emissions and potential risk to the nearby residential areas. The South Uranium Plant and Great Noligwa No. 8 Gold Plant were not recognised as important air pollution sources and contributed negligibly to the modelled SO_2 concentrations. The 1-hour (350 $\mu g.m^{-3}$) and 24-hour (125 $\mu g.m^{-3}$) SO_2 ambient air quality standards were exceeded for the stack and volume sources modelling scenarios and compliance was only achieved for the annual air quality standard of 50 $\mu g.m^{-3}$. The East Acid Plant modelled stack emissions complied with 1-hour and 24-hour averaging periods for prior (January – July 2007) and post-shutdown (September – December 2007) modelling scenarios.

The influence of meteorological conditions is evident as the modelled plume strikes mimic the study area's prevailing north-easterly winds and consequently sensitive receptors are impacted upon, though negligibly. Due to the nature and limited scope of this study, an in-depth analysis of the impact of meteorology on modelled concentration was not undertaken. Mainly the spatial distribution of SO_2 concentrations over the modelled area is discussed and temporal distribution of SO_2 concentrations is not dealt with in this report.

The model generally over-predicted along the plume centreline in the region of maximum impact and elsewhere. The AERMOD model significantly under predicted 1-hour and 24-hour maximum average concentrations for the stack (only) and stack and volume emissions at the nearby ambient monitoring station. The upwind location of the station could have influenced these results. Some of the differences between modelled and monitored data could probably be due to the SO_2 background emission levels which were not taken considered in this study. Moreover and more significantly, the under prediction by the model could be attributed to the fact that only the stack concentrations were modelled in detail as part of this study i.e. plant shutdown modelling scenarios which had comprehensive mass balance data.

The emission factors used for volume (fugitive) sources particularly at the East Acid Plant were not accurate and therefore largely under estimated. Fugitive emissions from the East Acid Plant are known to contribute significantly to the ambient SO_2 concentrations and fugitive sources were not modelled pre-and-post Acid Plant shutdown. The overall modelling results are in fact reflective of the under estimation of SO_2 concentrations from the Acid Plant. Annual maintenance shutdowns at this plant are particularly aimed at addressing fugitive emissions and therefore future modelling studies at this plant should certainly encompass an advanced emission inventory database inclusive of fugitive and area sources and possibly background SO_2 emissions sources observed to contribute to elevated emissions.

The AERMOD modelling system is an important regulatory tool for modelling the spatial distribution of priority pollutants e.g. sulphur dioxide from various sources on a local scale (<50 km). However, the ability to accurately model source contributions to pollutant concentrations is strongly dependant upon the model input data, in particular, the emission rates from point, volume and area sources even those that are complex to quantify. This will enable future modelling of the East Acid Plant emissions and other sources to be more accurate.

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Appendix 1: AngloGold Ashanti East Acid Plant Mass Balance Model Monstrance (Jacobs, 2007)