Regulating sulphur dioxide emissions from platinum smelters in South Africa

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Abstract

Air pollution is a major cause of mortality and morbidity globally. Sulphur dioxide (SO_2) emission is regulated because of its detrimental effects on health and the environment. More stringent SO_2 emission limits will be enforced from 01 April 2020.

This study aimed to evaluate the regulation of SO_2 emissions from platinum smelters in South Africa. The following objectives assisted in achieving the research aim:

- Understand the regulatory strategy to manage SO_2 emissions from platinum smelters.
- Assess ambient SO_2 levels in the Rustenburg region.
- Determine the contribution of platinum smelters to ambient SO_2 levels in the Rustenburg region.

To address these objectives, a literature review of SO_2 regulation was conducted. An air dispersion model was applied to assess ambient air SO_2 levels in the Rustenburg region and the impacts of platinum smelters on ambient air quality in the region were modelled.

The current environmental management approach focuses on command and control. All plants in the same industry must comply with more stringent emission standards that come into force on 01 April 2020. At most, the SO_2 10-minute average national standard was exceeded 23 times compared with the allowable 526 times, the SO_2 1-hour average national standard was exceeded 16 times compared with the allowable 88 times and the SO_2 24-hour average national standard was exceeded twice compared with the allowable 4 times. Ambient SO_2 levels in the Rustenburg region are within the allowable standards and platinum smelters are the major source of SO_2 in the area.

In the spirit of the National Environmental Management Act (Act no. 107 of 1998), which promotes participation of interested parties in environmental governance, application of a hybrid approach including other management strategies, such as public disclosure and air quality offsets, is recommended. This should increase economic viability and realise social and environmental sustainability.

Keywords: Sulphur dioxide, emissions, platinum smelters, South Africa

Opsomming

Lugbesoedeling is wêreldwyd een van die vernaamste oorsake van siektes en sterftes. Swaeldioksied (SO_2) word gereguleer aangesien dit inherent ‘n negatiewe effek op die omgewing en gesondheid het. Strenger beperkinge op SO_2 uitlatings gaan vanaf 1 April 2020 geld.

Die doel van hierdie studie is om te bepaal hoe die SO_2 vrylatings in Suid-Afrika by platinum smelterye gereguleer word. Die volgende doelwitte is daarom gestel:

1. Om die strategie wat gebruik word om die vrylatings van SO_2 by platinum smelterye te reguleer, te verstaan.
2. Om die SO_2- vlakke in die onmiddelike omgewing van die Rustenburgstreek te evalueer.
3. Om die bydrae van platinum smelterye tot die SO_2 – vlakke van die onmiddelike omgewing van die Rustenburgstreek te bepaal.

Literatuur oor SO_2 regulasies is bestudeer om die navorsingsdoelwitte te bereik. Die lugverspreidingsmodel is toegepas om die vlakke van $S0_2$ in die Rustenbergstreek te bepaal en die impak van platinum smelterye te modelleer.

Die huidige benadering tot omgewingsbeheer fokus op bevel en beheer. Alle aanlegte in dieselfde industrie moet dus voldoen aan strenger uitlatingstandaarde.

Die SO_2 10-minute gemiddelde nasionale standaard is hoogstens 23 keer oorskry vergeleke met die toelaatbare 526 keer. Die $S0_2$ 1-uur nasionale standaard is 16 keer oorskry vergeleke met die toelaatbare 88 keer. Die SO_2 24-uur nasionale standaard is 2 keer oorskry vergeleke met die toelaatbare 4 keer. Die SO_2 vlakke in die onmiddelike omgewing van die Rustenburgstreek val binne die voorgeskrewe lugstandaarde. Platinum smelterye is die vernaamste bron van $S0_2$ in die area.

In die lig van die Wet op Nasionale Omgewingsbestuur (Wet no. 107 van 1998) wat die deelname van betrokke partye in die bestuur van hulle omgewing aanmoedig, word ‘n gemengde benadering van verskillende bestuurstrategieë soos byvoorbeeld publieke openbaarmaking en lugkwaliteitteenwigte, aanbeveel. Hierdie benadering behoort ekonomiese lewensvatbaarheid en sosiale en omgewingsvolhoubaarheid tot gevolg te hê.

Sleutelwoorde: Swaeldioksied, uitlatings, platinum smelterye, Suid-Afrika

Preface

I would like to thank my research supervisor, Roelof Burger, and co-supervisor, Jan-Albert Wessels, for their continued support and guidance throughout this research project. I would also like to express my sincere gratitude to the Anglo American Platinum team of Nishi Haripursad, Hermanus Prinsloo and Bayanda Mncwango for assisting with provision of emission data. Thapelo Mathekga from the Bojanala Platinum District Municipality was instrumental in assisting with the emission inventory. To my wife, Gadihele, and my daughters, Ahanang and Tshegofatso, as well as my son, Otlile – thank you very much for allowing me time to pursue my studies.

This Master's degree is dedicated to my late grandmother Maria Ntshenya Mabaso (1928–1998).

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Abbreviations

ACP	Anglo Platinum Converting Process
AEL	Atmospheric Emission License
AERMOD	American Meteorology Society-Environmental Protection Agency Regulatory Model
APPA	Atmospheric Pollution Prevention Act No. 45 of 1965
BPDM	Bojanala Platinum District Municipality
BIC	Bushveld Igneous Complex
CAIA	Chemical and Allied Industries' Association
CAAA	Clean Air Act Amendments of 1990 (US)
ESP	Electrostatic precipitator
EU	European Union
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
hPa	Hecto Pascal
H_2SO_4	Sulphuric acid
IA	Integrated Assessment
MASP	Metropolitan Area of São Paulo
MEC	Member of Executive Council
NAAQS	National Ambient Air Quality Standards
NEMA	National Environmental Management Act 107 of 1998
NEMAQA	National Environmental Management Act No. 39 of 2004
NO_2	Nitrogen dioxide

NO Nitrogen oxide

NO_x Nitrogen oxides

PM Particulate matter

PPB Parts per billion

PPM Parts per million

PGMs Platinum group metals

PROCONVE Program for the Control of Air Pollution Emissions by Motor Vehicles

RSF Residential solid fuels

SCF Slag cleaning furnace

SEPA Scottish Environment Protection Agency

SO_2 Sulphur dioxide

SO_3 Sulphur trioxide

SO_x Sulphur oxides

tpd Tonnes per day

UG Upper Group

US United States

USEPA United States Environmental Protection Agency

WCM Waterval Converter Matte

WBPA Waterberg–Bojanala Priority Area

WDM Waterberg District Municipality

WHO World Health Organization

CHAPTER 1: INTRODUCTION

This chapter introduces the research by presenting an overview of the study as well as the theoretical background, the research aims and objectives, the limitations and the ethical considerations thereof. It concludes by giving an outline of the mini-dissertation.

1.1 Overview and theoretical background

Humans need clean air for good health and well-being. An assessment by the World Health Organization (WHO) in 2005 indicated that more than two million premature deaths each year could be attributed to the effects of urban air pollution. The developing nations carry most of the disease burden (WHO, 2005). An estimated 3.7 million deaths globally were attributed to ambient air pollution in 2012. Low- and middle-income countries accounted for about 88% of these deaths (WHO, 2014a). It has been observed that air pollution is amongst the major causes of mortality and morbidity (Lim *et al*., 2012).

Countries that undergo rapid industrialisation and urbanisation are confronted with the challenge of reducing air pollution while simultaneously maintaining economic growth. It is therefore important for these countries to adopt efficient and effective environmental policies (Kanada *et al*., 2013). Developed and developing countries are implementing stringent air quality controls for ambient air as a response to air pollution. In the absence of additional air quality legislation to that promulgated by 2005, there will be a global overall increase of more than 50% in pollutant emissions by 2030 in comparison to the 2005 baseline levels (Cofala, 2007; Rao *et al*., 2013).

The prevailing approach in environmental governance focuses on the achievement of ecological modernisation is the adoption of science-based policies. Environmental regulations – particularly air quality regulations – are based on science that offers an authoritative foundation for a regulatory response. Policy interventions ought to be substantiated by scientific evidence (Scott & Barnett, 2009). Air pollution problems in Western Europe and North America were addressed through stringent policies and coordinated measures that specifically targeted the reduction of sulphur dioxide (SO_2). However, emissions are rising in many developing countries across the world. In the Highveld industrial source area in South Africa, multiple exceedances of SO_2 critical levels have been observed. Damage to the environment will occur if appropriate control measures are not implemented and pollution emissions continue to increase (Josipovic *et al*., 2010).

In order to protect the environment, most government agencies have adopted a regulatory approach – also known as “command and control” – whereby standards are set for each significant pollutant and the set standards have the force of the law (Higley *et al*., 2001). In order to combat air pollution in the country, the South African government has implemented ambient air standards and strict point-source emission standards. Strict emissions standards are not intended to be a barrier to economic growth and social development as outlined in the National Environmental Management: Air Quality Act 39 of 2004 (NEMAQA).

An additional environmental strategy that has been implemented worldwide is environmental information disclosure, which is a form of civil-based tool. Environmental information disclosure complements command and control in two ways:

- Pollutants that are not included in the traditional regulations can be included in the information required for public disclosure.

- Public disclosure has been effective in managing pollution where environmental regulatory arrangements are few or where there is weak enforcement, particularly in developing countries (Tian *et al*., 2016).

In China, effective environmental disclosure in pollution control correlates with high indices in pollution information transparency. Lower pollutant levels are linked to greater pollution-control investment. Public pressure for the protection of the environment strengthens environmental disclosure in pollution reduction. No evidence was found to suggest that environmental regulation efficacy in pollution control was improved by environmental disclosure. However, results have shown that the most effective method of pollution control was observed when cities responded to public information requests (Tian *et al*., 2016).

Other environmental strategies applied globally are fiscal/market-based (e.g. emission charges and a deposit-refund system) and voluntary/agreement-based (e.g. ISO 14001 and Responsible Care) tools. All of these strategies are discussed in section 2.4.

Most of the mineral deposits in South Africa are found in the Bushveld Igneous Complex (BIC). The majority of the mining activities are found in the western limb of the BIC and this is where most of the platinum in the world is produced (Venter *et al*., 2012). The Merensky and Upper Group2 (UG2) ore reefs are mined for recovery of platinum group metals (PGMs). The Merensky reef is dominated by plagioclase and orthopyroxene, whereas the UG2 reef is dominated by chromite. In the BIC, PGMs and base metals are strongly linked with the sulphide minerals chalcopyrite, pentlandite and pyrrhotite. The processing of PGMs results in the inadvertent emission of SO_2, which is a pollutant of concern (Dzvinamurungu *et al*., 2013).

Platinum smelters, which fall under metallurgical industries that smelt and convert sulphide ore, are required to comply with SO_2 emission standards (South Africa, 2009; South Africa, 2010; South Africa, 2013a). The Anglo American Mortimer smelter (AAMS) was not compliant with the SO_2 emission standards that came into effect on 01 April 2015 and subsequently applied for postponement to comply with these SO_2 emission standards. The Department of Environmental Affairs (DEA) granted AAMS a postponement to comply (Amplats, 2015). More stringent SO_2 emission standards promulgated in March 2010 will be effective from 01 April 2020. Lonmin Platinum have already indicated that they will apply for postponement to comply with the 2020 SO_2 emission standards in the event of the company failing to comply by the proposed date. It is evident that current and future SO_2 emission standards are a challenge for the platinum smelting industry. No evidence was found that a previous study had been done to determine if point-source emission standards for platinum smelters in the Rustenburg area are environmentally, socially and economically sustainable. This study aims to fill that gap.

1.2 Research aim and objectives

It may be deduced from the background provided that SO_2 emissions levels are a serious environmental concern and the Regulator has subsequently implemented emission standards as an environmental governance tool to protect ambient air quality in South Africa. Some platinum smelters in the Rustenburg area will have to invest in technological upgrades to comply with current and future SO_2 emission standards. Abatement technology needs to be researched and commissioned before being implemented (Amplats, 2015; Lonmin 2015).

The Anglo American Mortimer smelter is not the only smelter that does not comply with the SO_2 emission limits that came into effect in 2015 (Amplats, 2015). Other platinum smelters are also likely to be unable to comply with the more stringent SO_2 emission limits by 2020 if abatement technology is not implemented. For this reason this dissertation aims to evaluate how SO_2 emissions from platinum smelters in South Africa are regulated. The following objectives were set to assist in achieving the aim:

(1) To understand the regulatory strategy to manage SO_2 emissions from platinum smelters.

(2) To assess the status of ambient SO_2 in the Rustenburg region.

(3) To determine the contribution of platinum smelters on ambient SO_2 levels in the Rustenburg region.

The importance of this study is underscored by the prominent role that platinum smelters play as anthropogenic point-source emissions of SO_2 and the inherent impact of SO_2 on human health and the environment. The scope of work will be limited to SO_2 emitted from the platinum smelters in the Rustenburg region. The study will only consider the direct impacts of SO_2 on ambient air quality and not the secondary impacts of SO_2 converting into small particulates and then impacting on PM2.5 (particulate matter with aerodynamic diameter less than 2.5 microns) and PM10 (particulate matter with aerodynamic diameter less than 10 microns). This is an important impact, but it does not fall within the scope of the present study.

1.3 Limitations of study and validity of data

The study area was limited to the platinum smelters in the Rustenburg area. The major limitation of the study was that some mining companies were reluctant to share emission data, particularly data required to model the impact of the sources. Most of the data were sourced from published documents, annual reports of mining companies, and reports from the Bojanala Platinum District Municipality and the North West Department of Rural, Environment and Agricultural Development.

The second limitation was that ambient air data used for modelling air quality could only be sourced from three ambient air stations owned by Bojanala Platinum District

Municipality. Ambient air data from the stations owned by mining companies are not easily available. Nevertheless, the ambient air stations used in this study are sited in townships where most receptors are based. The author assumes the study evaluated the area where sources have the greatest impacts.

The third limitation was that large uncertainties are associated with the emission factors used in air dispersion modelling and the author expects large spatial variability in ambient SO_2 concentrations. The author assumes the ambient air stations used in the study to be representative of the whole area.

The fourth limitation was that some data were not available from the monitoring stations due to maintenance issues for certain periods during the monitoring period. Modelled data were validated by comparison with data from the Anglo American Platinum ambient air stations as specified in their annual report.

1.4 Ethical considerations

The author upholds the ethical principles of accountability, respect, transparency, academic and scientific professionalism. The author has signed a code of conduct for registered scientists as per the South African Council for Natural Scientific Professions. This study was solely intended to advance academic research. As such, data obtained will be protected and will not be used for other purposes.

1.5 Structure of research

This dissertation has been structured as follows:

Chapter 1: Introduction

This introductory chapter gives the theoretical background of this research, the aim and objectives of the study, the factors that limited the study, validation of the data and ethical considerations, and concludes with an outline of the research.

Chapter 2: Literature review

This chapter provides a review of literature that is focused on sources of air pollution, impacts of SO_2, policies implemented locally and internationally to manage SO_2

emissions, environmental management approaches, platinum smelting processes and, finally, atmospheric dispersion modelling.

Chapter 3: Data and methods

The outline of the research design, the methods used to review literature and the empirical investigation are provided in this chapter. The dispersion model used to process the data is also described in this chapter.

Chapter 4: Results and discussion

In this chapter a review of literature pertaining to South African SO_2 emission regulatory requirements is conducted. Data from ambient air stations and the platinum smelters is processed in a dispersion model. The results of study are presented and interpreted.

Chapter 5: Conclusion

In this chapter conclusions are formulated based on the research aim and objectives.

1.6 Conclusion

The impact of air pollution was discussed in this introductory chapter. Regulatory responses towards air pollution and, more specifically, the response towards combating SO_2 emission were deliberated upon. Other environmental management tools, such as civil- and market-based tools, were outlined briefly. The aims and objectives, limitations of the study, ethical considerations of the author and finally the outline of the research were discussed. The literature review will be discussed in Chapter 2.

CHAPTER 2: LITERATURE REVIEW

In this chapter sources of air pollution are discussed in section 2.1. Specific focus is on anthropogenic sources as this research is based on platinum smelters as anthropogenic sources of SO_2. The sources and impacts of SO_2, as well as methods to remove SO_2 from the atmosphere, are discussed in section 2.2. Section 2.3 covers international policy strategies to manage SO_2 and section 2.4 discusses different environmental management approaches to managing the environment. Discussions on policy and environmental management approaches address objective 1 of this research, which is to understand the regulatory strategy to manage SO_2 emissions from platinum smelters. Section 2.5 describes platinum processing at Anglo American Platinum, Impala Platinum and Lonmin Platinum in Rustenburg as these processes contribute SO_2 into the ambient air in the study area. In section 2.6, atmospheric dispersion modelling is discussed as this tool is used to address objective 2 (assess the status of ambient SO_2 in the Rustenburg region) and objective 3 (determine the contribution of platinum smelters on ambient SO_2 levels in the Rustenburg region).

2.1 Natural and anthropogenic sources of air pollution

Air pollution can be caused by both human (anthropogenic) and natural actions. Natural and anthropogenic activities in South Africa have resulted in increased aerosol load (Piketh *et al.*, 1999a). Typically, atmospheric aerosol is composed of wind-blown dust particles, organic carbon, black carbon, sulphates, ammonium, nitrates and trace metals (Maritz *et al.*, 2015).

2.1.1 Natural sources of air pollution

Natural sources of air pollution include, among others, wind erosion, forest fires, volcanic eruptions, dispersion of pollen grains and the evaporation of organic compounds. During the dry season (May–September) in the summer-rainfall region of South Africa, wildfires are significant sources of particulate emissions (Korhonen *et al.*, 2014). The next section will focus on anthropogenic sources of air pollution as this dissertation focuses on anthropogenic sources of SO_2.

2.1.2 Anthropogenic sources of air pollution

Anthropogenic sources of pollution include, *inter alia*, industrial emissions, vehicle emissions, domestic combustion of fuels and controlled burning of vegetation. Almost 3 billion people depend on the combustion of residential solid fuels (RSF), such as wood, coal, charcoal, animal waste and agricultural residue as a primary source of energy (Bonjour *et al*., 2013). The burning of RSF is normally done in open fires or simple stoves with low combustion efficiencies causing significant emissions of aerosols (UNEP, 2011). The combustion of fuels is a source of aerosol emissions that impacts negatively on air quality (Lim *et al.*, 2012). Residential emissions account for 25% of energy-related black carbon emissions globally (Bond *et al.*, 2013).

Annually, the combustion of RSF in low- and middle-income countries is estimated to effect 4.3 million deaths (WHO, 2014b). It is well documented that RSF combustion has an adverse impact on human health through indoor air quality. However, few studies have quantified the impact of outdoor air quality on human health (Butt *et al.*, 2015). Atmospheric aerosols cause cardiopulmonary and respiratory diseases in humans, while environmental impacts include acid deposition and eutrophication (Gauderman *et al.*, 2004; Lazaridis *et al.*, 2002).

Central and southern Africa are two of the largest sources of biomass-burning aerosol in the world (Langmann *et al.*, 2009). Biomass burning is a significant source of air pollution in southern Africa, impacting negatively on air quality and climate change (Aurela *et al.*, 2016). Biomass-burning aerosol contributes significantly to the atmospheric aerosol load. It is considered to be a key source of reactive trace gases in the atmosphere (Vakkari *et al.*, 2014).

There are distinct dry and wet seasons in the interior of South Africa. The wet season is from mid-October to April and the dry season from May to mid-October. Large-scale biomass burning takes place during the dry season. An increase in pollutant levels is observed due to a decrease in wet deposition of pollutants (Venter *et al.*, 2012). Controlled burning of vegetation during the dry season (May–September) is a significant source of particulate emissions (Korhonen *et al.*, 2014). Local air quality is also heavily affected at night by domestic air pollution from informal and semi-formal settlements (Venter *et al.*, 2012). According to Swap *et al.* (2004) the impact of biomass burning plumes from southern Africa can be observed as far as Australia and South America. Furthermore, industrial emissions from tall stacks are released and lifted to the residual layer. The low, stable boundary layer during the night lessens the effect of industrial emissions on air quality (Korhonen *et al.*, 2014).

The anticyclonic recirculation in the South African Highveld and the overwhelming continental high pressure over the interior contribute significantly to the build-up of pollutants, particularly during the dry, cold winter season (June–August) and the early spring season (September–mid-October). During these periods, pollutants are trapped at several different heights by strong inversion layers, thus preventing vertical mixing. This phenomenon causes the concentration of atmospheric pollutants to increase near the land surface (Venter *et al.*, 2012). The build-up of pollutants in a local area causes harmful effects (Cooper, 2002).

In order to determine the impact of anthropogenic sources, an ambient air study was done at Botsalano Game Reserve in the North West province, South Africa (25.541° S, 25.754° E), where there are no major local anthropogenic sources (see Figure 2-1).

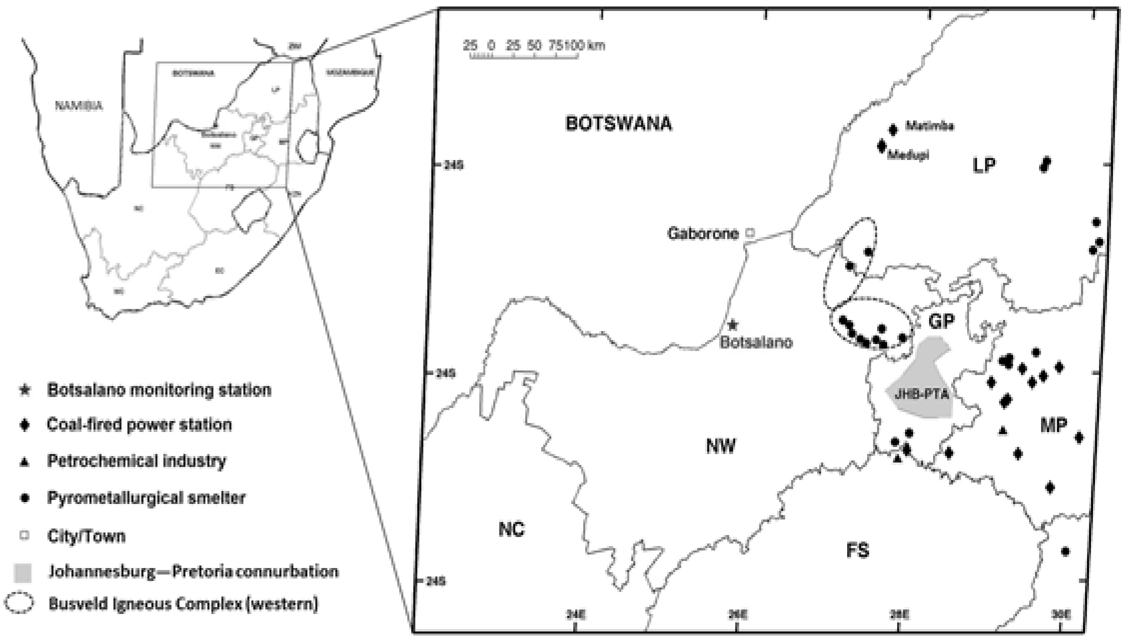

Figure 2-1: Botsalano ambient air measurement site and nearby sizeable air pollution point sources (Aurela *et al*., 2016).

The measurement site is located on the dominant anticyclonic circulation route of air mass movement and is situated downwind of the Medupi and Matimba power stations in the Waterberg area. East of Botsalano, in the western limb of the BIC, lie potentially the largest regional pollution sources, namely activities associated with large mining and pyrometallurgical platinum and chrome smelting.

The Botsalano air quality is largely affected by air masses that have travelled over several large point sources from the Matimba Power Station, a coal-fired power station, at Lephalale, as well as the platinum and silicon smelters near Polokwane, the Mortimer platinum smelter at Northam, and the platinum and ferrochrome smelters in the Rustenburg area. Compared with the background concentration at Botsalano, air masses from the Waterberg and Rustenburg areas increase the sulphate concentration by 14–37 times (Aurela *et al.*, 2016).

2.2 Sulphur dioxide in the atmosphere

Sulphur dioxide is a colourless gas at room temperature and a colourless liquid when pressurised or cooled. It is a highly soluble gas with a characteristic suffocating odour, very irritating to the eyes and respiratory tract, and it has a pungent, acid taste (Moeller *et al.*, 1984; Badenhorst, 2007). Sulphur dioxide is generated by the burning of any sulphur-containing material. The main source, by far, is fossil fuel combustion for electric power generation, although other industrial processes, such as non-ferrous metal smelting, can be sources in specific locations (Cooper, 2002). The present study focused mainly on pyrometallurgical processes resulting from gaseous emissions of SO_2 and fluorides that harm the environment (Hayes, 2003). In the platinum industry, SO_2 is produced during the smelting and converting process of sulphur-based matte. When released into the air, it can be converted to sulphuric acid (H_2SO_4), sulphur trioxide (SO_3) and sulphates (Badenhorst, 2007).

Sulphur dioxide emissions are associated with human health problems. The routes of exposure to the human body are primarily through inhalation and the skin and/or the eyes, nose and throat (Badenhorst, 2007). Substantial lung damage in humans is caused by SO_2 through the formation of H_2SO_4 and acid rain (Hayes, 2003). Particulate sulphates with absorbed SO_2 can penetrate deep into the lungs and induce severe health impacts. The impact that short-term, intermittent exposure to SO_2 has on animals is similar to that on humans except that animals are less susceptible. The upper respiratory tract readily absorbs SO_2 due to its solubility. Some bronchoconstriction occurs with exposure to concentrations above 1 ppm. Eye, nose and throat irritations occur when concentrations exceed 10 ppm. Sulphur dioxide stimulates mucus secretion, which is a characteristic of chronic bronchitis. One of the major effects of SO_2 on green plants is chlorosis (loss of chlorophyll). An additional effect on plants is plasmolysis (tissue collapse of many of the leaf cells). Sulphur dioxide effects can occur with either short exposure to high concentrations or long exposure to lower concentrations (Cooper, 2002).

The chief precursors of acid rain are SO_2 and NO_x, and their continued emission into the atmosphere has become a global concern (Cooper, 2002). Sulphur dioxide can be removed from the atmosphere through processes such as wet and dry deposition, oxidation, absorption by vegetation and by soil as well as dissolution into water, resulting in acidic compounds. Acidic compounds fall to the ground and then precipitate the corrosion of materials, increase the acidity of soils, rivers, lochs and streams, and subsequently affect the balance of ecosystems in these environments (SEPA). The dominant processes for removal of SO_2 are washout (wet-deposition) and absorption (WBK & Associates Inc., 2003). Wet deposition is made up of washout and rainout processes. Washout refers to the removal process within clouds, whereas rainout refers to removal by falling precipitation. Washout involves the formation of sulphate particles, coagulation and diffusional uptake, whereas rainout involves the diffusional uptake of particles by interception of falling raindrops. Wet deposition depends on factors such as precipitation type, frequency, duration, intensity, relative amounts of SO_2 to sulphate and particulate sulphate distribution size (Garland, 1978).

In Cape Town, South Africa, measurements that were taken in 1985/86 show that winter haze episodes in the city are caused by SO_x and NO_x emissions (Jury *et al.*, 1990). Under stable meteorological conditions, between May and August, Cape Town suffers from episodes of poor visibility as a result of brown haze caused by accumulated anthropogenic and natural aerosol particles and gas emissions (Gwaze *et al.*, 2007). This effect is caused by surface inversion layers that prevent vertical atmospheric mixing, thereby trapping the primary pollutants (Lourens *et al.*, 2011).

Although SO_2 is harmful, it also has beneficial uses in the production of H_2SO_4, as a preservative for some foods and drinks, as a bleach for textiles, disinfectant and also in the production of paper (Badenhorst, 2007; Moeller *et al.*, 1984). Sulphuric acid production is the most popular of these alternatives primarily due to lower production costs and the market demand for H_2SO_4, which is used as a chemical reagent (Hayes, 2003).

2.3 Sulphur dioxide policy

The increasing concentration of tropospheric SO_2, and the role it plays in changing the composition of the atmosphere as well as the detrimental effect it has on human health, on structures, and on aquatic and terrestrial biospheres is a concern internationally (Tayanc, 2000). The European Union (EU) has developed air pollution Integrated Assessment (IA) models, such as Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS). These models aim to determine cost-efficient policies that may minimise emissions in order to achieve the EU-wide targets for different air quality indicators, such as eutrophication, acidification, tropospheric ozone as well as primary and secondary particulate. The models collate data on pollutant sources (emission inventory), their contribution to concentrations in the atmosphere and human exposure, and provide information on potential emission reduction strategies and their respective implementation costs (Carnevale *et al.*, 2012).

Japan experienced serious environmental problems due to vigorous economic development in the 1950s and 1960s. However, the country reduced air pollution by implementing high standards in policy systems and environmental technologies (Kanada *et al.*, 2013). In China, during the period 2006–2010, national SO_2 levels in ambient air were reduced through the implementation of a SO_2 control policy by 13–15% compared with the 2005 level. The reduction was achieved primarily by installation of flue gas desulphurisation in coal-fired power stations. On 29 July 2011, the government of China published new emission standards for thermal power plants in order to reduce the emissions for the achievement of 2015 air quality standards (Wang *et al.*, 2014).

In 2012, in the Metropolitan Area of São Paulo (MASP), Brazil, mobile sources accounted for 37% of SO_x in the atmosphere. A number of policies have been introduced since the 1980s to reduce emissions by industries in the São Paulo state. Sulphur dioxide in the ambient air was reduced through action taken by industries to change from using oil to electric power to generate energy. In 1986, through the implementation of the Brazilian Program for the Control of Air Pollution Emissions by

Motor Vehicles (PROCONVE), limits were set for vehicle emissions. In 1992, a reduction of approximately 70% was observed for regulated emissions. Regulation of the sulphur content of fuel resulted in the availability of diesel S50 (sulphur content of 50 parts per million [ppm]) in 2012 and, by 2013, diesel S10 (with a sulphur content of 10 ppm) was also available (Carvalho *et al.*, 2015).

On 20 November 2013, Sasol launched 10 ppm ultralow sulphur turbodiesel (ULS 10ppm) on the South African market. This fuel enables the engine to run more efficiently and produces less harmful exhaust emissions. ULS 10ppm is the lowest sulphur-content diesel available in South Africa and complies with international standards for cleaner fuel specification (Sasol, 2013). This is a positive move by Sasol as diesel containing 500 ppm sulphur is still permitted in South Africa. It is encouraging that companies are voluntarily reducing sulphur emissions beyond legal requirements.

In 2007 the State of São Paulo's government implemented rules for the amplification and installation of new facilities in accordance with the local level of regular pollutants. Through PROCONVE in recent decades there has been a significant drop in the threshold of emissions by both new light-duty and heavy-duty vehicles. This happened despite an unprecedented fleet growth of more than 100% in the last decade (Carvalho *et al.*, 2015). Since 1989 in Santiago de Chile, Chile, there has likewise been policy implementation to improve air quality in the city. Ambient air data taken from 1983 showed a downward trend in SO_2, which is consistent with the implementation of policy to lower the sulphur content of fuels (Jorquera, 2002).

In India, GAINS was used to analyse air quality regulations for the city of Delhi. The study found that under the current policy, Delhi would not meet the recommended PM2.5 concentrations for National Ambient Air Quality Standards (NAAQS) even by the year 2030. In order to achieve PM2.5 ambient air concentrations, stringent policy control for the net flow of air pollution from transboundary sources may be effective in reducing pollution levels in Delhi (Dholakia *et al.*, 2013).

It is the author's opinion that the same measure of transboundary control should be applied to all pollutants and not only limited to PM2.5 when formulating a policy control. This is supported by a study done by Jenner and Abiodun (2013), which showed that emissions from the Mpumalanga Highveld in South Africa are linked to ambient sulphur in the city of Cape Town. Some of the SO_2 emitted in the Highveld is transported at the

700 hectopascal (hPa) level towards the Indian Ocean and some is transported at low levels towards Cape Town. Piketh *et al.* (1999b) also allude to the fact that highly stable vertical atmospheric conditions and complex circulation patterns enhance the accumulation of pollutants below 700 hPa. Sulphates, specifically, are transported in anticyclonic patterns of air flow over thousands of kilometres towards the Indian Ocean at about 30° S.

2.4 Environmental management approaches/tools

This dissertation focuses on the regulation of SO_2 as a management tool to prevent air pollution. It would be prudent to look at environmental management approaches/tools available to manage SO_2 emissions.

Environmental management follows the Deming cycle of planning, doing, checking and acting by managers of activities and governing agents, and pertains to green and brown environmental elements (Strydom & King, 2009). Environmental management goes beyond the management of natural resources to include the political and social issues as well (Barrow, 2006). Environmental governance is achieved by means of different environmental approaches (Sterner, 2003). The different environmental management approaches can be divided into the following groups:

- Command and control
- Fiscal/market-based
- Civil-based
- Voluntary/agreement-based

Section 2.4.1 to 2.4.4 will discuss the different environmental approaches and section 2.4.5 will summarise the strengths and weaknesses of each approach.

2.4.1 Command and control

Command and control regulation has been the dominant policy response towards environmental pollution and degradation since the 1970s (Sinclair, 1997). Regulatory authorities in South Africa use various types of command and control tools ranging from permits, licenses, authorisation directives, codes of practices, ambient air standards and emissions standards, among others (Hanks, 1998; du Plessis and Nel, 2011). Administrative and/or criminal sanction is meant to be used to enforce legal compliance. However, there has been inadequate enforcement of these laws for environmental non-compliances.

The situation changed in the 1990s when industry felt that command and control was costly, inefficient and did not stimulate innovation. This criticism led to the development of alternative environmental management tools (Sinclair, 1997). Developed countries shifted away from command and control in governance (policing) towards cooperation. This has led to the introduction of a number of softer alternative instruments (Sterner, 2003). However, command and control remains one of the main strategies for protecting the environment.

2.4.2 Fiscal- or market-based tools

Fiscal instruments are sometimes referred to as market-based instruments (MBIs) or economic-based instruments. National Treasury (2006) define fiscal instruments within the context of environmental management as policy instruments that use price mechanisms to rectify environmentally-related market failures. Fiscal instruments use monetary measures to ensure that pollution is avoided and, if that is not possible, then at least minimised. Tools such as environmentally-related taxes, emissions charges, resource charges and deposit-refund systems are used as fiscal instruments (National Treasury, 2006). The use of fiscal instruments has gained popularity in many parts of the world as they are considered to play an important role in improving environmental management and governance (September, 2011).

2.4.3 Civil-based tools

Civil-based tools focus on the social side of environmental management and are based on legislation such as the Constitution, the Bill of Rights, National Environmental Management Act 107 of 1998 (NEMA) and other sectoral environmental laws (Nel & du Plessis, 2001). Civil-based tools include measures to empower, educate, inform and co-opt civil society to be part of the environmental management process (Nel & Wessels, 2010). Examples of civil-based tools are public disclosure, green rights, private prosecution, class action, protection of whistleblowers, ecolabelling and beneficial cost awards (Nel & du Plessis, 2001). The next section will focus on public disclosure as one of the civil-based tools.

2.4.3.1 Environmental public disclosure

One of the civil-based mechanisms is environmental public disclosure. In Romania, Article 31 of their constitution gives persons unrestricted right to access information of public interest. Disclosure of data ensures that members of the public have the necessary information in order to participate meaningfully in policy and decision-making processes (Petrescu-Mag *et al.*, 2014). Similarly, in South Africa, the Promotion of Access to Information Act, 2000 (Act 2 of 2000, PAIA) ensures the public's right to access information.

In 1992, Canada introduced the National Pollutant Release Inventory (NPRI). This marked the emergence of a new strategy to regulate industrial pollution in that country. In contrast to the traditional permit-based regulation, the NPRI does not require mandatory emission limits, but rather requires facilities to track pollutant emissions and report those emissions to a public-accessible national database. This system empowers the public to scrutinise polluters and influence the behaviour of polluters and official regulators both informally and formally (Simmons, 2013). Similarly, South Africa introduced the National Atmospheric Emission Information System (NAEIS), which also requires emitters to report emissions, and no emission limits have been set (South Africa, 2015b).

A study was done in China on 533 Chinese listed companies to determine the relationship between corporate environmental performance and environmental disclosure. The results indicated a nonlinear relationship between corporate environmental performance and environmental disclosure. From a stakeholder's or investor's point of view, it is difficult to differentiate between a good and poor environmental performer based purely on the level of environmental disclosure (Meng *et al*, 2014). A legal framework with enforceable penalties is required to promote environmental disclosure for more sustainable development.

2.4.4 Voluntary tools

Voluntary tools are based on self-regulation by the companies and buy-in from the employees. These tools encourage industries to set environmental goals and make their own arrangements based on their circumstances to meet these set goals. The use of voluntary tools ensures that environmental issues are raised in corporate decision-making (Karamanos, 2001). Examples of voluntary tools include ISO 14001, the Responsible Care Initiative, the King Codes on Corporate Governance, the Forest Stewardship Council Scheme and the Global Reporting Initiative.

Voluntary agreements seldom operate in isolation from other policy instruments such as financial gains or related legislation. It is subsequently difficult to evaluate the influence of voluntary agreements while excluding other factors (Solsbery & Wiederkehr, 1995). Voluntary and regulatory strategies usually work together as complementary strategies (Jimenez, 2007). Policy-makers have turned to voluntary approaches by encouraging industries to take voluntary actions. Voluntary agreements are considered as more flexible, effective and less costly than the traditional regulatory approach (Arimura *et al.*, 2008). The next section will focus on offsets as one of the voluntary tools.

2.4.4.1 Offset program

Compensation for environmental damage due to development emerged in the USA and Europe in the 1970s. Offset programs have become efficient mechanisms for environmental management. These programs are used internationally within the biodiversity field to manage environmental damage. Around the globe, policy tools such as biodiversity offsets, wetlands mitigation, carbon trading, habitat banking, mitigation banking and species banking are widely used to mitigate environmental harm (Lapeyre *et al.*, 2015). With regard to the present study, offset programs can be important tools where platinum smelters do not meet point-source limits. The smelter can then implement offset programs to achieve positive ambient air.

Rustenburg is developing rapidly due to mining activities in the area. In order to facilitate economic development without compromising the environment, section 39(c) of NEMAQA makes provision for the application of the best practicable environmental options to mitigate pollution. Section 43(m) of NEMAQA also makes provision for the application of any other matters necessary for the protection of air quality. To that effect, the DEA published draft guidelines for air quality offsets (South Africa, 2015a).

Offsets are not intended to replace legal obligations where point-source emission standards cannot be met, but are to be used as an additional tool to achieve long-term environmental protection. Offsets are to be used as interventions to counterbalance adverse atmospheric emissions by delivering a positive net ambient air quality within the affected airshed. Therefore, intended offsets should be based on improving ambient air quality in the airshed. The intended offset should not be “like for like”, i.e the objective of the offset must be to mitigate the effects of pollutants of concern in a particular area and not necessarily from a specific facility (DEA, 2014).

Anglo American Platinum’s Mortimer smelter was granted an exemption to comply with the SO_2 emission standards that came into effect in March 2015 (Amplats, 2015). Lonmin (2015) made reference to the legal provision for postponement to comply with 2020 SO_2 emission standards in the event that the company may not be able to comply with the 2020 emission standards. It is the author’s assertion that legal provision should be made for exemption from compliance to point-source emission standards where offset programs yield a positive net effect on ambient air quality. Metallurgical facilities that do not meet or are unlikely to meet future deadlines set for SO_2 emission standards will then be able to consider implementing air quality offset projects to mitigate negative ambient air quality.

2.4.5 Strength and weaknesses of environmental management approaches

Each management approach/strategy has strengths and weaknesses, which have been summarised in Table 2-1.

Table 2-1: Strengths and weaknesses of different environmental management approaches.

	Management approach			
	Command and control	Fiscal or market -based	Civil-based	Voluntary
Advantages/ Strengths	·Reduce compliance costs ·Recognition and reward · ·Dependability ·Clarity ·Major driver of private-sector compliance ·Compliance or non-compliance is readily detectable ·Works well for: • Single media issues • Control of point-source emissions • Waste management • Protection of endangered species • Fosters new technologies	·Cost-effective ·Efficient ·Internalise environmental costs ·Flexibility ·Stimulate innovation ·Encourage continual improvement ·Act as incentive for the development of more cost-effective pollution control technologies ·Provide greater flexibility in the choice of technology or prevention strategy ·More cost-effective in achieving agreed levels of pollution ·May provide government with a source of revenue, which may be used to support environmental or	·Industry can improve reputation and stakeholder relations ·Prove due diligence ·Capitalise on market advantages ·Illustrate leadership ·Whistleblowers ·Greater knowledge on environmental issues ·Public waste inventories ·General awareness of communities ·Cleaner production	·Stimulate industry competiveness ·Illustrate leadership ·Enhance reputation and relations with stakeholders ·More cost-effective and efficient

		social initiatives ·These tools act as incentives for innovative practices.		
Disadvantages/ Weaknesses	·Can lack public support ·High administrative costs ·Not effective for delivering policy choices ·Not efficient in delivery at lowest cost ·Too information intensive ·Universal rules do not work ·Absence of incentives ·Often result in adversarial legal combat ·May result in administrative complexities ·Proliferation of laws ·Insufficiently flexible to deal with dynamic situations ·Often media specific ·Difficult to deal with trans-media impact ·Depend on politicians to prosecute ·Inflexible and require a lot of enforcement and regulation from the regulating authorities	·No guarantee that environmental objectives will be met ·Lack of experience ·Lack of knowledge and awareness ·Lengthy implementation ·May require additional administrative resources ·Determination of proper prices is a difficult political task ·Environmental valuation is not properly understood by the structures in power ·Depend heavily upon the availability of sufficient information to enable economic actors to make rational decisions in their self- interest	·Non-standardised and verified information lacks credibility, comparability and reliability ·Lack public awareness ·Stakeholders and I&A not always fully engaged ·No public pollution inventories ·Lack of ecolabelling ·Financial constraints	·No guarantee that environmental objectives will be met ·Free-riders ·Can lack public buy-in and support

(Source: Hanks, 1998; Nel and Wessels, 2010).

As can be observed from Table 2-1, reliance on a single strategy is misguided because none of the approaches can address all environmental problems in all contexts due to the inherent strengths and weaknesses of each strategy. The best approach is therefore to have a hybrid of instruments tailored to harness the strengths of an individual mechanism and to compensate for their weaknesses by using other instruments to address a specific policy goal. This does, however, not necessarily mean that all combinations of instruments will always be better than a single-instrument approach (Gunningham and Sinclair, 1999). It is therefore the author's contention that regulators and emitters should consider all environmental management approaches to mitigate SO_2 emissions.

2.5 Platinum process in South Africa

South Africa is the world's largest producer of platinum, accounting for 78% of the world's platinum production in 2013 and generating US$7 billion in sales (Rauch & Fatoki, 2013; Chamber of Mines, 2015). Three of the world's largest platinum-producing companies, namely Anglo American Platinum, Impala Platinum and Lonmin Platinum, have platinum smelting operations in the Bojanala Platinum District Municipality (see Figure 2-2).

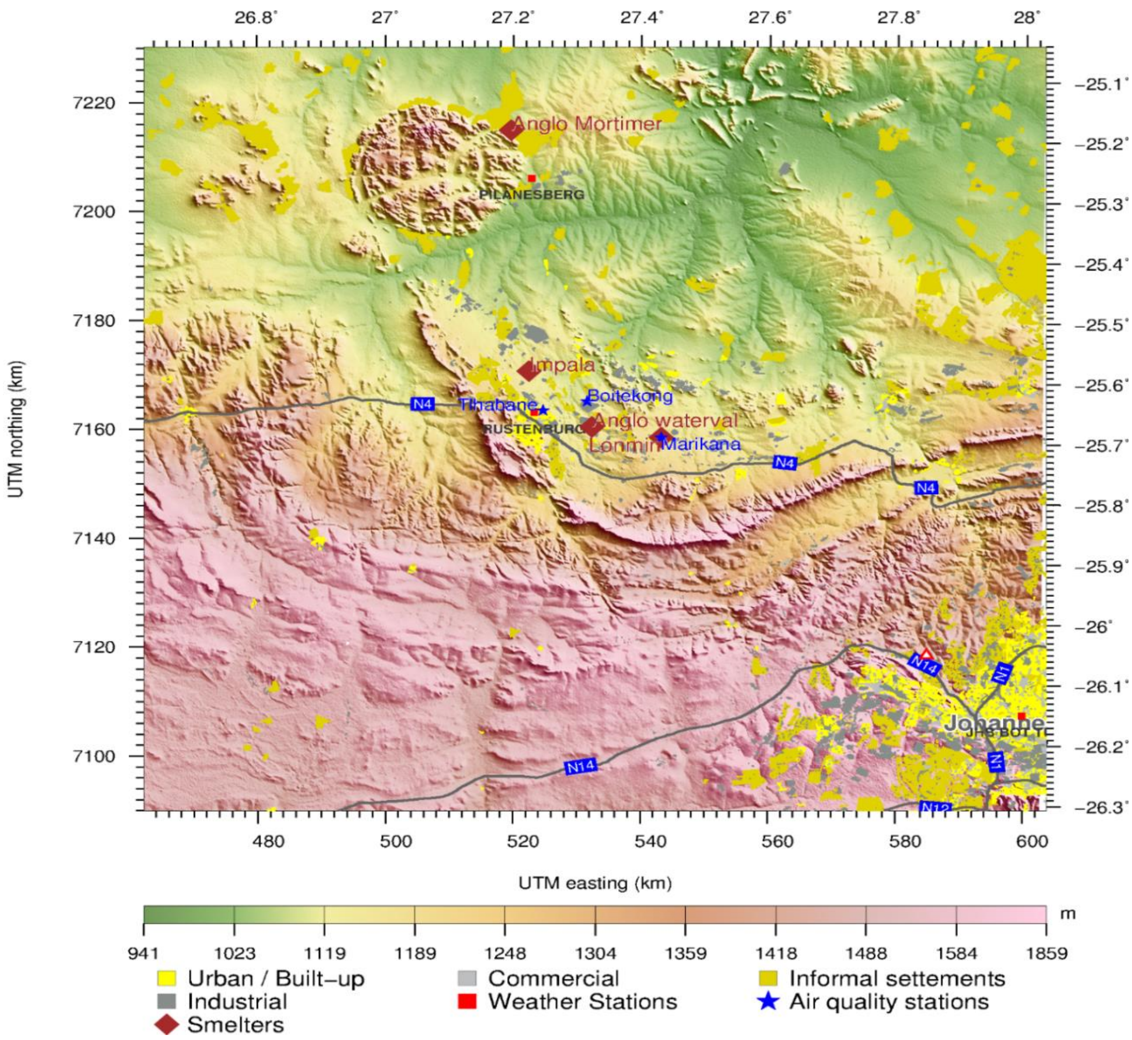

Figure 2-2: Map indicating location of platinum smelters in the Bojanala Platinum District Municipality, South Africa.

The next three sections will briefly outline how platinum is produced by the three mining houses.

2.5.1 Anglo American Platinum limited (Amplats)

Amplats is the largest primary producer of PGMs, accounting for about 40% of the world's newly-mined platinum (Amplats, 2013). In 1967 the Board of Rustenburg Platinum Mines decided to move from blast furnace smelting to electric furnace smelting in order to avoid high SO_2 emissions from the blast furnace process. The South African government at that time was introducing strict anti-pollution laws that would make it costly to control SO_2 emissions (Mostert & Roberts, 1973). Currently, the company has three smelters in South Africa, namely the Waterval smelter in Rustenburg, the Mortimer smelter near the town of Northam and the Polokwane smelter in Polokwane.

Both the Waterval and Mortimer smelters are located in the western limb of the BIC, in the Bojanala Platinum District Municipality in the North West province. The Polokwane smelter is situated in the eastern limb of the Bushveld Complex in the Limpopo province (Hundermark *et al.*, 2011; Airshed Planning Professionals, 2013).

The Waterval smelter process flow is shown in Figure 2-3. The Mortimer and Polokwane smelter process flow sheets are much simpler and consist of drying, primary furnace, off-gas, slag and matte handling unit operations. The wet concentrate from the concentrators is dried in flash driers at each of the smelters before being fed into primary furnaces. At the Waterval smelter the furnace matte is tapped and then granulated, whereas at the Mortimer and the Polokwane smelters the furnace matte is cast and crushed. At Mortimer and also partially at the Waterval smelter, a concentrate recycle is generated by milling and floating the furnace slag, whereas at Polokwane and partially at the Waterval smelter the furnace slag is stockpiled directly. In the Anglo Platinum Converting Process (ACP) the furnace matte from all the smelters is upgraded by the removal of iron (and sulphur) to form Waterval Converter Matte (WCM). The converter matte is sent to the Matte Concentrator (MC) plant at Rustenburg Base Metals Refineries (RBMR) for further separation of base metals and PGMs. Slag from the converter is recycled at the Slag Cleaning Furnace (SCF) to recover base metals and PGMs. Matte from the SCF is recycled to the ACP, whereas the slag from the SCF is recycled to the concentrators (Hundermark *et al.*, 2011).

The three smelters handle off-gases from various furnaces differently. The pollution abatement equipment at the Mortimer smelter comprises dry electrostatic precipitators. The Polokwane smelter makes use of high-temperature bag-house filters. At the Waterval smelter the gas from the primary furnace is cleaned by firstly passing it through ceramic filters, secondly by a wet cleaning system and finally through a low-strength acid tower plant. The ACP off-gas is treated by wet cleaning, followed by passing through a double-contact, double-absorption acid plant where 98% H_2SO_4 is produced. Off-gas from the SCF is cleaned in the wet venture scrubber (Hundermark *et al.*, 2011).

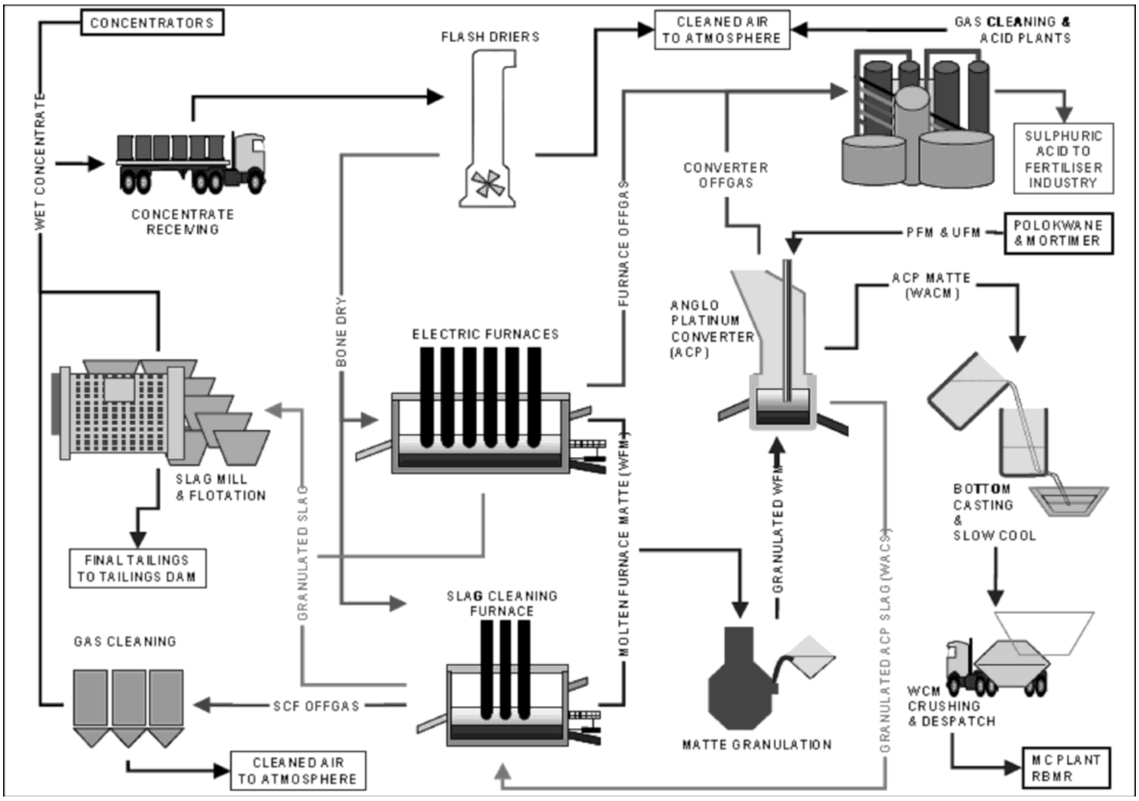

Figure 2-3: Schematic process flow sheet for the Waterval smelter (Hundermark, 2011).

2.5.2 Impala Platinum Holdings Limited (Implats)

Impala Platinum is the second-largest platinum producer in the world. Its primary operations are based approximately 25 km north of Rustenburg in the North West province. The refining plant is located in Springs in the East Rand, Gauteng province. Ore (Merensky reef and UG2 reef) from underground is delivered to the concentrators via the rail network. Merensky ore is crushed in ball milling circuits containing single-stage hydrocyclone classification. The process is followed by bulk sulphide flotation in a single-stage circuit. UG2 plant processes UG2 ore in two primary autogenous mills. The mill discharge is screened to separate the silicate-rich fraction from chromite-rich fraction. Ninety percent of the PGMs are found in the fines – high-grade chromite-rich material that reports to the undersize. The other 10% of the PGMs are found in the low-grade silicate-rich material, which reports to the screen oversize (Coetzee, 2006).

A simplified flow sheet of the Impala Platinum smelter is shown in Figure 2-4. In order to maximise water efficiency and to facilitate blending, the flotation concentrate is treated through a thickening circuit together with the toll concentrate. The thickened product is transferred to the coal-fired Niro-technology spray-drying units. The bone-dry material is then pneumatically transferred to the silo. The material is then fed into the electric furnace to concentrate the sulphide. The sulphide matte, which is rich in PGMs, is further concentrated by removing iron in the Peirce-Smith converters (Coetzee, 2006).

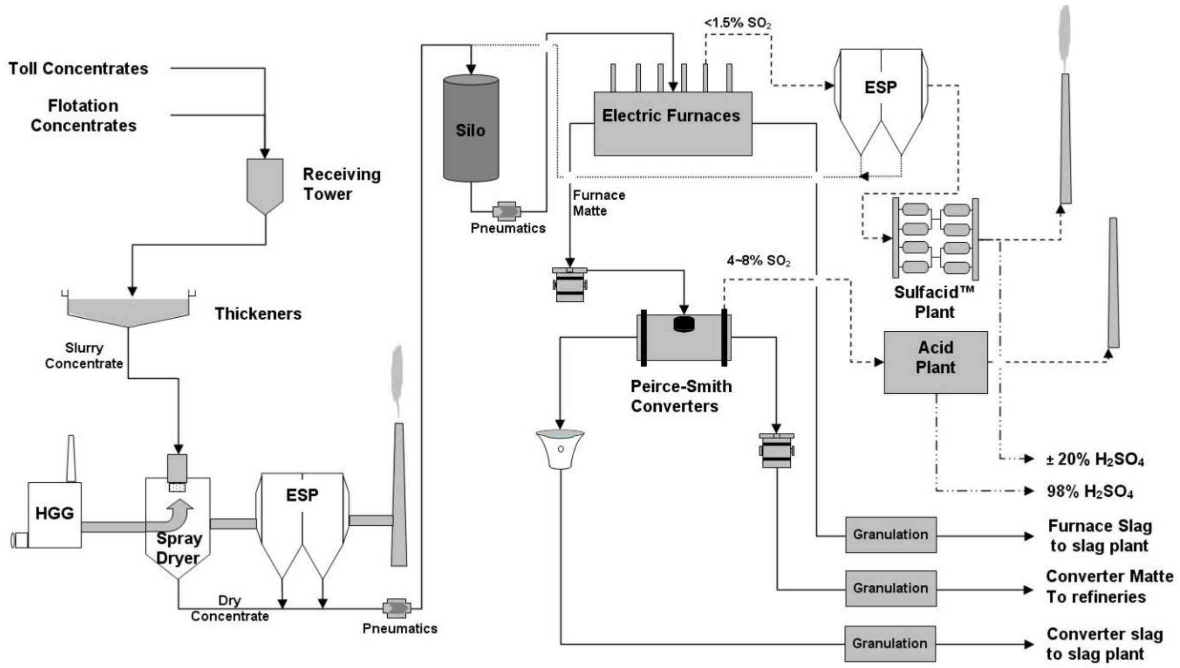

Figure 2-4: Simplified process flow sheet for the Impala Platinum smelter (Coetzee, 2006).

Off-gases from the electric furnace generally have a SO_2 concentration below 15 000 ppm. These gases are treated in a Sulfacid process, which uses activated carbon as a catalyst to produce a weak H_2SO_4 solution with a concentration of less than 20% H_2SO_4.

The off-gases from the Peirce-Smith converters are much stronger, with SO_2 concentrations of 40 000–80 000 ppm. Conventional Lurgi-designed acid plant is used to treat the off-gases to produce a 94–98% H_2SO_4 product. Sulphuric acid products are traded to fertiliser producers (Coetzee, 2006).

2.5.3 Lonmin Platinum

Lonmin is the world's third-largest primary producer of PGMs. Most of the operations are found at Marikana, near Rustenburg, on the western limb of the BIC. There is one mine near Polokwane on the BIC's eastern limb. Lonmin operates small concentrators located close to the mine shafts in order to maintain a more stable input into the concentrators and also to allow optimisation for high recoveries at low mass pulls (Eksteen *et al.*, 2011). Both the Merensky and UG2 ore reefs are processed to produce PGMs (van Schalkwyk *et al.*, 2011). Larger quantities of UG2 concentrates are smelted. UG2 contains low base metal concentrations (copper [Cu], nickel [Ni] and cobalt [Co]), which leads to PGM-concentrated furnace matte containing low matte falls and smaller amounts of converter slag SO_2. It is therefore not economically feasible to invest in slag-cleaning furnaces or acid plants because by-products formed (Cu, Ni, Co and H_2SO_4) are not significant enough to make recoveries economically feasible. Lonmin focuses on the rapid removal of Ni, Cu, Co, iron and sulphur in order to produce medium-grade Cu cathode, crude $NiSO_4$ and a high recovery of high PGM grade (65–75%) concentrate. This is done in a short pipeline time and with low metal-in-process inventories (Eksteen *et al.*, 2011).

In order to lower the iron and sulphur concentrations of the matte, the flotation concentrate from the mine is smelted, followed by Pierce-Smith converting as shown in Figure 2-5 (van Schalkwyk *et al.*, 2011). Slurry from the UG2 and Merensky concentrators is pumped to the blending tanks and then transferred to a filter feed tank. Internal smelter recycle material is also fed into the blending section. The big difference in concentrate composition is buffered by homogenisation in the large filter feed tank. The filtered material is then transferred to the drying section where there is a fluid-bed flash dryer. The flash dryer is the preferred technology because of its high energy utilisation efficiency and high availability. Material from the flash dryer is fed into the furnaces (Eksteen *et al.*, 2011).

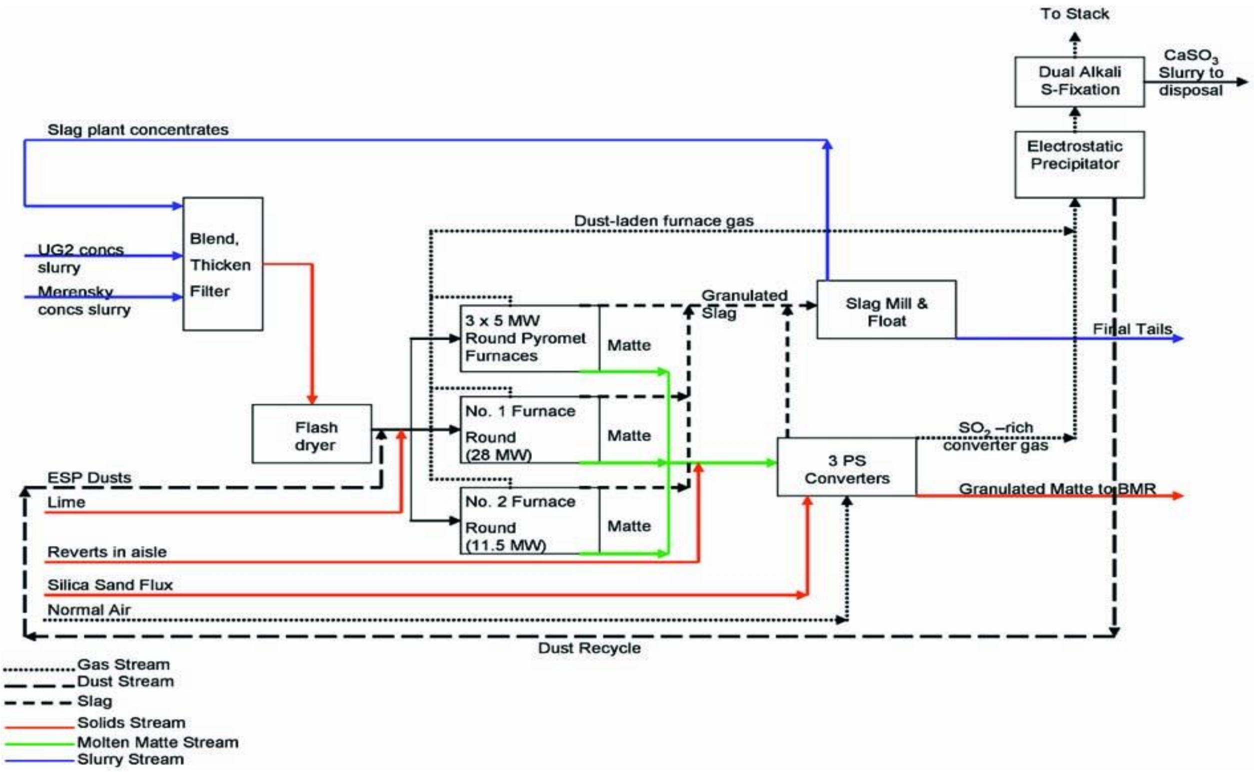

Figure 2-5: High-level block process flow sheet for the Lonmin smelter (Eksteen *et al.*, 2011).

The Lonmin smelter has five furnaces, namely a 28 MW, three-electrode circular Furnace No. 1, 11.5 MW, three-electrode circular Furnace No. 2, and three 5 MW three-electrode circular furnaces. The typical furnace and converter matte composition is shown in Table 2-2.

Table 2-2: Typical furnace and converter matte composition of the Lonmin smelter.

Component	Typical furnace matte composition, mass (%)	Typical bulk finished converter matte composition, mass (%)
Ni	18.5	48
Cu	11.0	29
Fe	39.0	1.0
Co	0.5	0.35
S	29.0	21

(Source: Eksteen *et al.*, 2011).

Good furnace efficiency is indicated by matte in slag typically ranging between 0.10% and 0.16% depending on feed grade, electrode immersion and hearth power density. Furnace matte is fed to three identical Peirce-Smith converters by means of scoops. Silica, which acts as a fluxing agent, and reverts are added to the converters through a top vibrator feeder system. The converter has three blowers able to provide an airflow of on average 13 000 Nm^3/h each. Temperatures in the converter are controlled to remain below 1 270 °C. Converters and blowers function on two-in-service and one-on-standby mode. The Lonmin acid plant does not require a minimum SO_2 concentration; hence, there are no water-cooling panels in the converter hoods (Eksteen *et al.*, 2011).

Pollution abatement equipment at the smelter consists of a variable-throat scrubber, two-field dry electrostatic precipitator (ESP) and a concentrated mode Dual Alkali plant. Converter off-gases bypass the ESP while furnace off-gases are passed through the ESP. Off-gases from the ESP are then combined with converter off-gases at the feed to the variable-throat scrubber. More than 98% of the particulates are removed on the ESP. In case of the off-gas completely bypassing the ESP, the variable-throat scrubber is capable of handling the full particulate load. The Dual Alkali plant was installed primarily to handle high-end SO_2 concentrations, which could not be easily managed by pure lime-based scrubbing. Acid plant operations are not conducive to the low end of the SO_2 concentration. These factors, coupled with the fact that Lonmin smelts UG2 with low sulphide content, and sulphur emissions require effective capture, made it uneconomical to invest in a sulphuric acid plant (Eksteen *et al.*, 2011).

In the Dual Alkali plant, a solution of Na_2SO_3 and NaOH absorb SO_2, forming mostly $NaHSO_3$ as a product. Precipitation of $CaSO_3$ and $CaSO_4$ is forced by addition of slaked lime ($Ca(OH)_2$) while $NaHSO_3$ is regenerated to NaOH and Na_2SO_3.. The Dual Alkali plant produces a final product of $CaSO_3/CaSO_4$ mixture in a ratio of around 80/20 (Eksteen *et al.*, 2011).

2.5.4 South African platinum industry and SO_2

Mining is an important economic sector of South Africa. According to Ololade and Annegarn (2013) mining is inherently unsustainable because mineral resources are non-renewable. The environmental and social costs brought about by platinum mines in Rustenburg are high compared to low economic benefits to surrounding communities (Ololade & Annegarn, 2013). Jones (2011) alluded to the fact that SO_2 emissions from

platinum smelters' furnaces and converters are difficult to avoid when using a sulphur-based matte. Steyn (2005) mentioned that the dominant pollutants in the Rustenburg area are particulates and SO_2, which act synergistically in affecting the environment and human health adversely. According to Buthelezi (2009) the high SO_2 concentration in the Rustenburg area is due to emissions from platinum smelters in that region.
In 2013 a total of 74 880 t SO_2 was released into the atmosphere by the three biggest producers of platinum in South Africa. Table 2-3 indicates the amount of SO_2 emitted by Amplats, Implats and Lonmin Platinum in 2013.

Table 2-3: SO_2 quantities emitted by Amplats, Implats and Lonmin Platinum in2013

Company	SO_2 emitted in 2013
Amplats	52 000 t
Implats	18 536 t
Lonmin Platinum	4 344 t (11.9 t/day)

(Source: Amplats, 2013; Implats, 2013; Lonmin, 2013).

Lonmin's emission of 11.9 t SO_2 per day is lower than the Atmospheric Emission License (AEL) permissible emission limit of 17.9 t/day prescribed for Lonmin Platinum (AEL discussion is included in section 3.7). The average concentration was 889 mg/Nm^3 against the industry limit of 3 500 mg/Nm^3 –(Lonmin, 2013). At Anglo American Platinum operations, the Waterval smelter SO_2 emissions averaged 14.88 t/day against the permitted level of 20 t/day; the Polokwane smelter averaged 20.15 t/day against the permitted level of 25 t/day and the Mortimer smelter averaged 17.31 t/day against the permitted level of 24 t/day (Amplats, 2013). The Impala Rustenburg smelter emitted 5 832 t/annum (15.98 t/day) from a Company group total of 18 536 t/annum (Implats, 2013).

The Anglo American Platinum Mortimer and Polokwane smelters have applied for postponement to comply with the stricter SO_2 emission standards which were promulgated in March 2010 and came into effect on 01 April 2015 (Further discussion on emission standards is covered in section 3.7 below) (Amplats, 2013; Mncwango, 2013; Airshed Planning Professionals, 2013). Lonmin is researching technology that will enable the company to meet stringent SO_2 emission standards that will be effective as of April 2020 (Further details on Lonmin AEL compliance is discussed in section 4.3.3 below) (Lonmin, 2015). These are clear indications that there is a concern regarding current and future SO_2 emissions standards for the platinum smelters.

2.6 Atmospheric dispersion modelling

Air pollutants are disposed by release into the atmosphere. The atmosphere has limited capacity to disperse highly concentrated streams of gaseous pollutants, depending on geographical and local meteorological conditions, such as wind direction, wind speed, and atmospheric stability (Cooper, 2002). For example, in Santiago de Chile, Chile, the airshed is strongly influenced by the season with winter ambient air values rising as high as four times the summer values, indicating that the atmospheric conditions limit the dispersion of the pollutants (Jorquera, 2002).

In most parts of southern Africa the mean atmospheric circulation is deep and stably anticyclonic throughout the year at a geopotential height of 800 hPa (see Figure 2-6). On average this occurs 500 m above mean altitude of the interior plateau surface. The stable discontinuities and stable conditions in the lower troposphere control the formation of the African haze layer. On non-rainy days, the haze layer forms a blanket over southern Africa at 500 hPa at an altitude of 5–6 km. The main components of the haze layer over South Africa are aeolian dust (derived from crustal material, soil and surface sand), sulphur from industrial processes, biomass-burning products and marine aerosols (Preston-Whyte & Tyson, 1988; Piketh *et al.*, 1999a; Piketh *et al.*, 1999b).

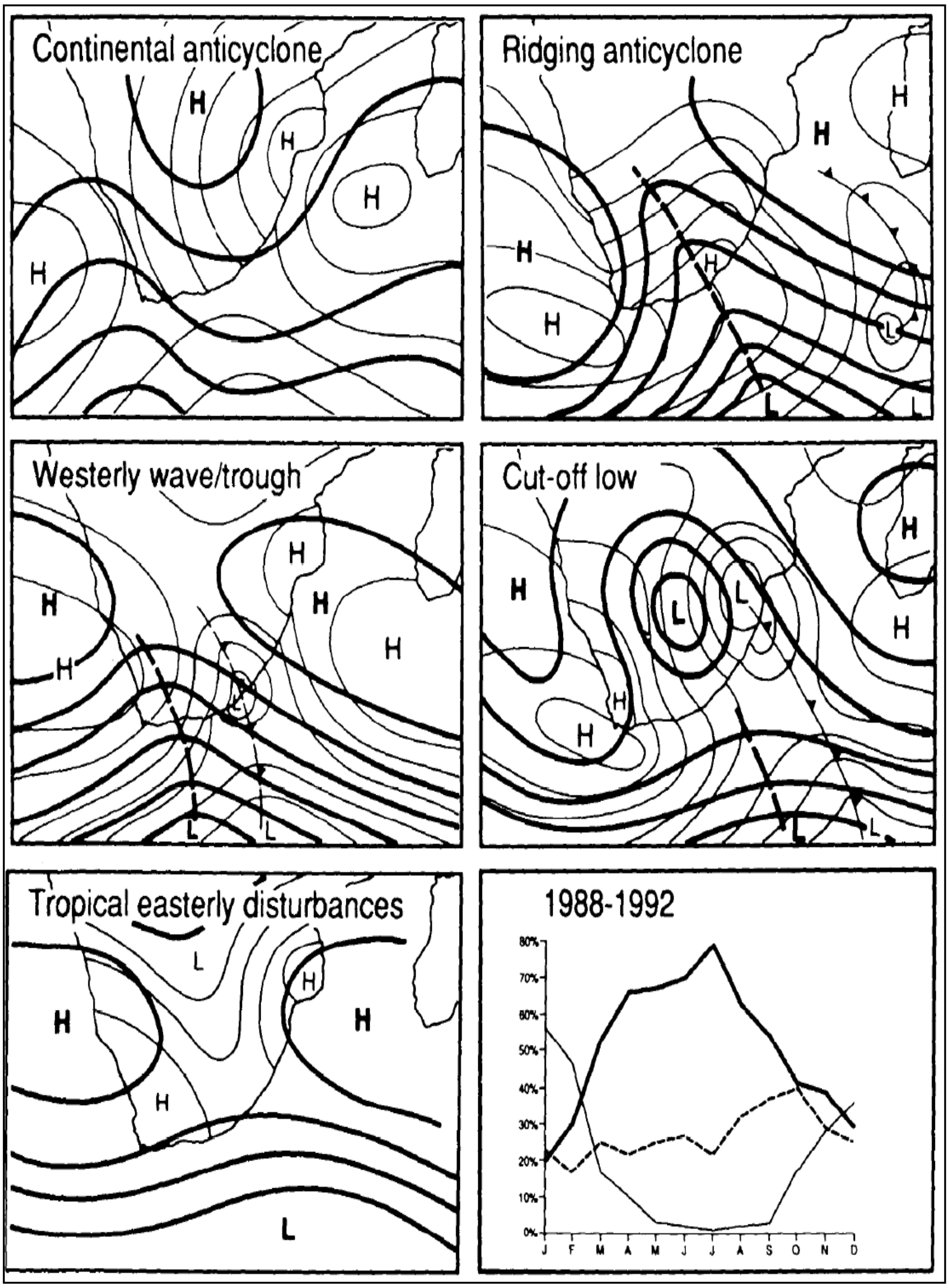

Figure 2-6: Dominant synoptic circulation types affecting southern Africa and their frequency of occurrence over a five-year period (1988–1992) (Preston-Whyte and Tyson, 1988).

Dispersion occurs when a continuous stream of pollutants is released into the atmosphere, rises, then bends over to travel with the mean wind and becomes diluted as it is carried away from the source. The plume of pollutants disperses from its centreline both in horizontal and vertical directions. Figure 2-7 depicts the physical stack height (h), the plume rise (Δh), and the effective stack height (H) of a bent-over plume (Cooper, 2002).

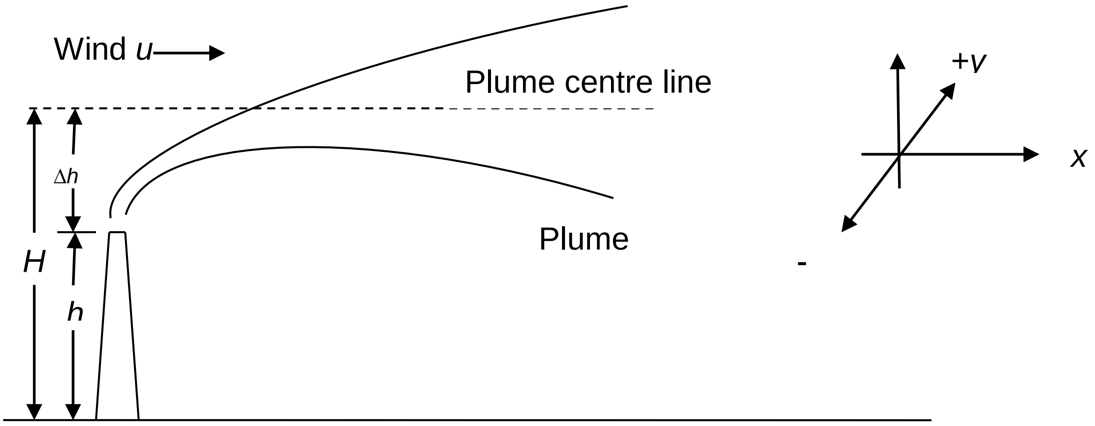

Figure 2-7: The spreading of a bent-over plume (Cooper, 2002).

Dispersion modelling applies mathematical equations to determine pollutant concentrations at different locations based on the atmosphere, dispersion, chemical and physical processes within the plume (Holmes & Morawska, 2006; UJ, 2007). Models by their nature are imperfect representations and are subject to many potential inaccuracies. However, modelling is essential because:

(i) It enables estimation of the impacts of a facility to be built in future.

(ii) Comprehensive measurements could be orders of magnitude more expensive than modelling and would also still be subjected to errors.

(iii) In a case involving multiple emission sources, modelling is the only practical approach when the objective is to apportion the impacts of an individual source.

(iv) Modelling is not 100% accurate but is reproducible. It is an important tool for assessing and comparing alternatives (Cooper, 2002).

2.6.1 The Gaussian model

The double Gaussian equation (Equation 2.1) models the dispersion of a nonreactive gaseous pollutant from an elevated source in both the *y* and *z* directions and predicts the steady-state concentration at point (*x*, *y*, *z*) located downwind from the source:

$$C = \frac{Q}{2\pi u\sigma_y\sigma_z} \exp\left(\frac{-1}{2}\frac{y^2}{\sigma^2_y}\right)\left\{\exp\left(\frac{-1}{2}\frac{(z-H)^2}{\sigma^2_z}\right) + \exp\left(\frac{-1}{2}\frac{(z+H)^2}{\sigma^2_z}\right)\right\}$$

Equation 2.1

where

C = steady-state concentration at a point (*x*, *y*, *z*), µg/m^3

Q = emission rate, µg/s

σ_y, σ_z = horizontal and vertical spread parameters, m (these are functions of distance, *x*, and atmospheric stability)

u = average wind speed at stack height, m/s

y = horizontal distance from plume centreline, m

z = vertical distance from ground level, m

H = effective stack height ($H = h + \Delta h$, where h = physical stack height and Δh = plume rise, m) (Cooper. 2002).

A view of the double Gaussian distribution in the plume, portrayed by Equation 2.1, is presented in Figure 2-8.

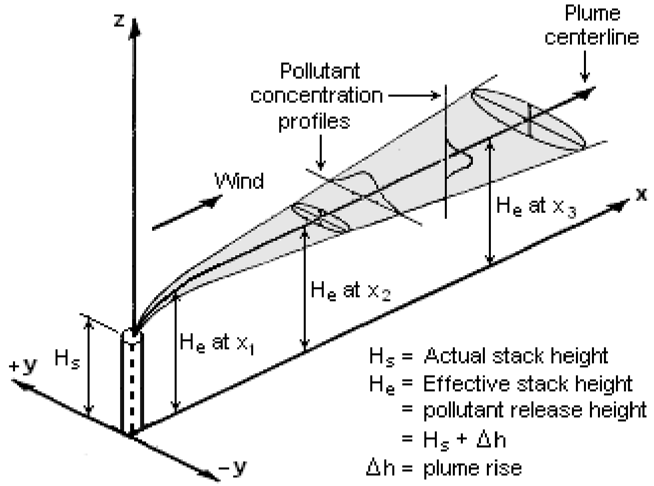

Figure 2-8: Visualisation of a buoyant Gaussian air pollutant dispersion plume

The double Gaussian equation indicates that:

1. The downwind concentration is directly proportional to the source strength, *Q*.
2. σ_y, σ_z, which are dispersion parameters, increase with increasing atmospheric turbulence. This implies that unstable conditions decrease the downwind concentration.
3. As the effective stack height increases, the maximum ground-level concentration decreases (Cooper, 2002).

Modelling of emissions is not only essential for designing cost-effective mitigation measures to achieve acceptable levels of air quality, but is also important in assessing the future chemical composition of the atmosphere and the potential impacts (Cofala, 2007). As stated, these models are subject to many potential inaccuracies. Good judgement should therefore be applied when interpreting modelling results (Cooper, 2002).

The American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) was developed for regulatory applications by the American Meteorological Society and the United States Environmental Protection Agency (Caputo *et al.*, 2003). It is one of the recommended regulatory dispersion models for South Africa, others being SCREEN3, AERSCREEN, CALPUFF and SCIPUFF (South Africa, 2014). AERMOD is a steady-state plume model that assumes the concentration distribution to be Gaussian in both the vertical and horizontal directions in a stable boundary layer (SBL) (USEPA, 2004). It is designed to model short-range (<50 km) air pollutant dispersion from stationary industrial sources. It is an advanced plume model that incorporates boundary layer theory, understanding of turbulence and dispersion, and handles terrain interactions. AERMOD is (1) capable of providing reasonable ambient air concentration estimates under a spectrum of conditions with minimal discontinuities, (2) user-friendly with reasonable input requirements and (3) capable of accommodating changes as scientific knowledge evolves (USEPA, 2003). For these reasons AERMOD was chosen as the dispersion model for the present research.

2.7 Concluding remarks on findings from literature review

There are various anthropogenic and natural sources of SO_2 pollution. One of the main sources of anthropogenic SO_2 pollution in South Africa is platinum smelters. Platinum smelters produce SO_2 during the smelting and converting processes of sulphur-based matte. Sulphur dioxide has detrimental effects on humans, structures as well as terrestrial and aquatic ecosystems.

Globally, countries are implementing laws to combat SO_2 emissions. South Africa is implementing strict emissions standards as a command and control strategy to curb SO_2 pollution. In light of the published evidence summarised in section 2.4, it would be advisable for platinum smelters to utilise a combination of environmental instruments to manage emissions, such as voluntary management instruments (e.g. ISO 14001), agreements with government (e.g. air quality offsets) and public disclosure (participation). By doing so, the industry may have a valid claim for provision to be made to apply for exemption from unachievable command and control (legal) requirements.

Dispersion modelling is a useful tool used to estimate pollution source impacts at different locations far from the source. Modelling is imperfect due to inherent inaccuracies; hence, modelling results must be interpreted with care.

CHAPTER 3: DATA AND METHODS

This chapter describes the design of this research, the method used to review literature and the empirical investigation. The AERMOD atmospheric dispersion model was used to quantify the results for this research. The model description is provided in this chapter.

3.1 Research design

To address the research objective, a research design that integrated the different components of the study in a coherent manner was adopted. The process involved data collection, monitoring, measurement, processing and data analysis.

Creswell (2003) identified three aspects that are central to the design of research:

- Knowledge claims made by the researcher
- Strategies of the inquiry that inform the procedures
- Methods used for data collection analysis.

Elements of inquiry	**Approaches to research**	**Design processes of research**
Alternative knowledge claims	Qualitative	Questions/objectives
Strategies of inquiry	Quantitative	Data collection
Methods	Mixed methods	Data analysis
		Write-up
		Validation

Figure 3-1: Elements, approaches and design processes of research

Figure 3-1 indicates that elements of inquiry/research combine to form different research approaches. The approaches are then translated into processes in the research design (Creswell, 2003).

A mixture of qualitative and quantitative modes of enquiry was used to answer the research questions. Qualitative results were based on information from a literature review as presented in sections 2.3 and 2.4. The quantification of results was based on monitored/measured results and computerised modelling results as provided in sections 2.5 and 2.6 (Kumar, 2014).

3.2 Methodology

A literature review was done to address objective 1, which entails understanding the regulatory strategy to manage SO_2 emissions from platinum smelters. Ambient air monitoring data and the AERMOD dispersion model were used to address the research objectives 2 and 3, which focus on assessment of the current status of ambient SO_2 in the Rustenburg region and determination of the contribution of platinum smelters to ambient SO_2 levels in the region.

3.3 Methods used for review of literature

A literature review entails a process of identifying material to be included in the research and synthesising the material in order to analyse their contribution. The process aims to identify what has already been done in the field of a particular research topic to consolidate existing knowledge and to identify omissions or gaps. Authors conducting a literature review should be careful in their choice of sources and not merely choose sources that will confirm their own world views or hypotheses. This will lend undue bias to preferred hypotheses (Grant & Booth, 2009).

There are many types of reviews, such as a scoping review, literature review, critical review, mapping review and meta-analysis. Each type of review has perceived strengths and weaknesses. A literature review was chosen for the present study primarily because the process involves the review of published literature that already has a degree or measure of credibility because it has been subjected to peer review (Grant & Booth, 2009).

Peer-reviewed material for inclusion in the literature review was mainly sourced from scientific journals. In addition, annual reports of individual companies were used as sources of information. These annual reports had been subjected to external audits before publication.

3.4 Method used for the empirical investigation

The assessment of the current status of ambient SO_2 in the Rustenburg region and the impact of platinum smelters on ambient SO_2 levels were estimated by means of atmospheric dispersion modelling. Dispersion modelling was used to determine pollutant concentrations at different locations based on source information, emission rates, meteorology and topography (Holmes & Morawska, 2006; UJ, 2007). Literature and available emission data for the platinum smelters in the Rustenburg area were used to model dispersion of SO_2 in the atmosphere using the AERMOD dispersion model.

3.4.1 AERMOD dispersion model

An air dispersion model was constructed based on ambient air monitoring data from the Marikana, Tlhabane and Boitekong ambient air monitoring stations. The positions of these monitoring stations are in townships where most people live and where the SO_2 emissions have the greatest impact. Raw data for the period January to December 2013 from the monitoring stations was sourced from the South African Weather Services (SAWS).

The three stations record data for the following meteorological parameters: (1) wind speed and wind direction, (2) ambient temperature, (3) relative humidity, (4) ambient pressure and (5) solar radiation. In addition to meteorological data, the following pollutants were also measured: (1) SO_2, (2) carbon monoxide (CO), (3) nitrogen oxide (NO), (4) nitrogen dioxide (NO_2), (5) nitrogen oxides (NO_x), (6) ozone (O_3) and PM10. To ensure a relatively stable temperature inside the monitoring station, a temperature sensor was installed in each station (RLM, 2013). Emission factors were used in the dispersion modelling. It must be noted that large uncertainties are associated with the emission factors. Processed monitoring data were compared with South African ambient air standards.

AERMOD consists of the dispersion model and two pre-processors (see Figure 3-2), namely the AERMOD meteorological pre-processor (AERMET) and the AERMOD mapping program (AERMAP).

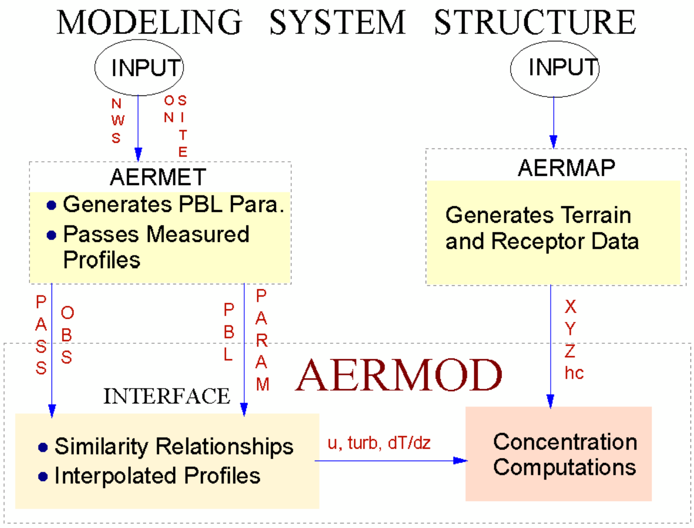

Figure 3-2: AERMOD modelling system structure (USEPA, 2004).

AERMET supplies the model with the meteorological data required to characterise the planetary boundary layer (PBL) (USEPA, 2003; USEPA, 2004). The PBL is strongly affected by the Earth's surface because it is the lowest part of the atmosphere. Variation in surface temperature causes temporal and spatial alterations in the dynamics of the PBL. In air pollution models, the upper height of the PBL is crucial because it determines the vertical space and, therefore, the volume of pollutant mixing, which is important for concentration assessment (Korhonen *et al.*, 2014).

AERMET is used to characterise the status of the surface and mixed layer, including the vertical structure of the PBL. It uses meteorological data required by the model to calculate boundary layer parameters, such as friction velocity and mixing height. Surface characteristics, such as surface roughness, albedo, and the Bowen ratio, and standard meteorological observations, such as wind direction, wind speed, temperature and cloud cover, are fed into AERMET. AERMAP is a terrain pre-processor that characterises the terrain and generates the receptor grid for the model. The gridded terrain is used to calculate a representative terrain-influence height associated with each receptor location (USEPA, 2003; USEPA, 2004).

3.4.1.1 Modelling steps

AERMOD View version 8.8.9 was used to model SO_2 dispersion in the present study. The modelling procedure is outlined below and followed the British Columbia Ministry of Environment guidelines for dispersion modelling (BCME, 2008).

Step 1: Setting the context

The scope of the study was defined to include platinum smelters in the Bojanala Platinum District Municipality, Rustenburg. The location of the four smelters is indicated in Figure 2-2.

Step 2: Characterisation of the sources/contaminant

The pollutant of interest, based on the scope identified in step 1, was SO_2. All potential point sources of SO_2 from the platinum smelters in the area were identified, including stack parameters such as coordinates, height of release above ground, diameter at stack tip, gas exit temperature , gas exit velocity and emission rates. In order to protect individual companies' information, details of the emission inventory could not be published.

Step 3: Characterisation of the physical and meteorological setting

The domain was identified in which air quality impacts were assessed. A total modelling domain coverage of 50 km by 50 km with grid resolution of 500 m by 500 m was used. The modelling domain included urban areas, informal settlements, industrial and commercial areas. The domain was chosen on the basis of the distance from the sources of concern. The receptors of interest were areas where there are human settlements and industrial activities. Buildings, terrain contours, imported terrain region and a uniform Cartesian grid receptor were chosen for this modelling run. Meteorological data for the three ambient air stations was sourced from SAWS.

Step 4: Prepare input files and run models

Surface and profile meteorological data were processed before being fed into the AERMET processor. Augmented upper air data were sourced from ERA-Interim[1]. Data was gridded to produce, firstly, a variety of three-hourly surface parameters that describe weather as well as land-surface conditions and ocean-wave , and secondly, six-hourly upper-air parameters (wind, temperature, humidity, surface pressure and ozone) covering the troposphere and stratosphere (Dee *et al.*, 2011). The system included a four-dimensional variation analysis with a 12-hour analysis window. The spatial resolution of the data set was approximately 80 km on 60 vertical levels from the surface up to 0.1 hPa. A multivariate, spatially complete and coherent record of the global atmospheric circulation data is provided (Dee *et al.*, 2011; ECMWF, 2015).

Step 5: Prepare output

Output files were chosen to produce hourly, 24-hourly and annual average SO_2 concentrations. Contour plot, threshold violation and rank files can also be produced but these parameters were not part of the present study.

3.5 Concluding remarks regarding design and methodology

The research design and methodology (approach) followed were explained in this chapter. In summary, a literature review was used to answer research objective 1, which was to understand the regulatory strategy to manage SO_2 emissions from platinum smelters. Ambient air monitoring results and the AERMOD air modelling were used to answer research objectives 2 and 3, which are to assess the current status of ambient SO_2 in the Rustenburg region and to determine the contribution of platinum smelters to ambient SO_2 levels in the region. The input, processing and output data of the AERMOD dispersion model were discussed.

[1]ERA-Interim is the most recent global atmospheric reanalysis produced by the European Centre for Medium Range Weather Forecasts (ECMWF) (Dee *et al.*, 2011). It is a global atmospheric reanalysis from 1979 and continues to be updated in real time. The data assimilation system used to produce ERA-Interim is based on a 2006 release of the Integrated Forecast System, cycle 31r2 (IFS [Cy31r2]). It models information and observations of many different types combined in an optimal manner to produce a consistent, global best-estimate of the various atmospheric, wave and oceanographic parameters (ECMWF, 2015).

CHAPTER 4: RESULTS AND DISCUSSION

This chapter aims to achieve the research objectives outlined in section 1.2. Results from the literature review and dispersion modelling are presented and interpreted. A literature review of South African SO_2 emission regulatory requirements is done to address research objective 1, which is to understand the regulatory strategy to manage SO_2 emissions from platinum smelters. Data from three ambient air monitoring stations in the Rustenburg area is processed for air dispersion modelling to address research objective 2, which is to assess the status of ambient SO_2 in the Rustenburg region. Modelled data from the three ambient air monitoring stations is compared with reported data from eight other ambient air monitoring stations in the vicinity. Emission inventories from the platinum smelters are subjected to air dispersion modelling to address research objective 3, which is to determine the contribution of platinum smelters to ambient SO_2 levels in the Rustenburg region.

4.1 Understanding the South African regulatory strategy for the management of SO_2 emissions

Every industry and organisation is governed by laws, regulations and court decisions (Barnard *et al.*, 2005). South Africa has developed robust air quality legislation (Thambiran & Diab, 2011). Air pollution was previously governed by the now defunct Air Pollution Prevention Act 45 of 1965 (APPA). Under APPA, processes that caused air pollution were classified as scheduled processes and a Registration Certificate was required to operate such processes. For example, a process for the manufacture of H_2SO_4 or processes in which sulphur trioxide is evolved were regulated as H_2SO_4 processes. The Act did not explicitly regulate SO_2; however, it included a section that regulated noxious or offensive gases. The Act focused on controls that were source-based, rather than receptor-based. APPA was repealed because acceptable air quality could not be achieved in South Africa (South Africa, 1965; Naiker *et al.*, 2012).

In the new dispensation, following the first democratic election in 1994, a new era of environmental management was heralded. Section 24 of the Constitution of the Republic of South Africa, 1996 (RSA) provides everyone with the right to an environment that is not harmful to their health or well-being and "to have the environment protected for the benefit of present and future generations through reasonable legislative and other measures" (South Africa, 1996). NEMA section 2 requires development to be socially, environmentally and economically sustainable. NEMA section 2 further promotes the participation of all interested and affected parties in environmental governance. Section 28 of NEMA requires all parties to take reasonable measures to prevent pollution or to minimise and control such pollution if prevention is not possible. NEMA section 24 requires the Minister/Member of the Executive Council (MEC) to identify activities that may not commence without environmental authorisation due to the potential impact on the environment (South Africa, 1998).

NEMAQA was promulgated to protect ambient air quality by providing reasonable measures for the prevention of air pollution and ecological degradation. NEMAQA promotes the sustainable development principle that is enshrined in the Constitution and NEMA. The Act not only focuses on air pollution sources but also places emphasis on the receptor, which is the receiving environment (South Africa, 1965; South Africa, 2004; Naiker *et al.*, 2012; UJ, 2007).

Government Gazette No. 33064, dated 31 March 2010, published regulations for listed activities (and associated emission standards) that have or may have detrimental effects on the environment due to atmospheric emissions. The listed activities were further amended on 22 November 2013 in Government Gazette No. 37054. These regulations were promulgated in terms of NEMAQA section 21. Sulphur dioxide emitted from all metallurgical industries during the smelting and converting of sulphide ore was identified as listed activity 4-16, and emission standards for SO_2 have been included in the promulgated emission standards (South Africa, 2013a). Table 4-1 summarises the emission standards for SO_2 emissions from the smelting and converting of sulphide ores processes in South Africa.

Table 4-1: SO_2 emission standards for smelting and converting of sulphide ores.

Pollutant	Concentration (mg/Nm^3)	Plant status
Sulphur dioxide (Feed SO_2 < 5% SO_2)	1200	New [2]
	3500	Existing [3]
Sulphur dioxide (Feed SO_2 > 5% SO_2)	1200	New
	2500	Existing

(Source: South Africa, 2013).

Section 22 of NEMAQA prohibits any person from commencing with a listed activity without an Atmospheric Emission License (AEL). When considering an application for AEL, section 39 of NEMAQA requires the licensing authority to take the following into consideration:

- Relevant emission standards set for ambient air and the point source
- Pollution that is likely to be caused by the listed activity
- The impact of that pollution on ambient air quality, social conditions, economic conditions, health and cultural heritage
- Best practicable environmental options that take into account the ambient air quality, social conditions, economic conditions, health and cultural heritage (South Africa, 2004).

Section 43 (1) of NEMAQA requires the AEL to specify the items listed in Table 4-2.

[2] Any plant or process where an application for authorisation in terms of NEMA was made on or after 01 April 2010.

[3] Any plant or process that was legally authorised to operate by 01 April 2010 or any plant where an application for authorisation in terms of NEMA was made before 01 April 2010.

Table 4-2: Contents of an Atmospheric Emission License.

Item	Condition
(a)	Listed activity that has been issued
(b)	Premises where it has been issued
(c)	Person to whom it has been issued
(d)	Period for which the license is valid
(e)	Name of the licensing authority
(f)	Review period
(g)	Maximum allowed volume, amount, emission rate or concentration of pollutant that may be discharged to the atmosphere. The license should specify permissible rates under normal and abnormal conditions.
(h)	Other operating requirements relating to non-point sources or fugitive emission
(i)	Point-source emission measurement and reporting requirement
(j)	On-site ambient air quality measurement and reporting requirement
(k)	Penalties for non-compliance
(l)	Greenhouse gases measurement and reporting requirement
(m)	Any other matter required for the protection of air quality

(Source: South Africa, 2004).

The AEL is a legal tool aimed at protecting the emissions from the listed activities. Holders of an AEL have legal obligations to comply with conditions in the AEL.

In order to give effect to NEMAQA, national ambient air quality standards (NAAQS) were published on 24 December 2009 in Government Gazette No. 32816. Due to its inherent environmental and health impacts, SO_2 was classified as one of the criteria pollutants. Other criteria pollutants included in the NAAQS are NO_2, PM10, PM2.5, ozone, benzene, lead and carbon monoxide. Table 4-3 lists the NAAQS for SO_2 (South Africa, 2009; South Africa, 2012b).

Table 4-3: National ambient air quality standards for SO_2.

Averaging period	**Concentration**	**Permitted frequency of exceedance**
10 minutes	500 µg/m^3 (191 ppb)	526
1 hour	350 µg/m^3 (134 ppb)	88
24 hours	125 µg/m^3 (48 ppb)	4
1 year	50 µg/m^3 (19 ppb)	0

(Source: South Africa, 2009).

One of the strategic infrastructure projects outlined in the national development plan 2030 is to unlock economic opportunities in the North West province and accelerate the construction of the Medupi power station at Lephalale, in the Waterberg District Municipality (WDM). The planned expansion projects in the WDM and Bojanala Platinum District Municipality (BPDM) pose risks to ambient air quality, leading to the declaration of the Waterberg–Bojanala Priority Area (WBPA). The Minister of Environmental Affairs declared Waterberg–Bojanala a national air quality priority area on the basis that the ambient air quality within the WDM in the Limpopo province may exceed the NAAQS in the near future, and transboundary ambient air movement between the WDM and the BDM may result in a significant negative impact on air quality in both areas (South Africa, 2012a; South Africa, 2013b). As noted in the WBPA draft air quality management plan (AQMP), total SO_2 emissions in the priority area are about 397 000 t/annum. Sulphur dioxide concentrations recorded at the ambient air monitoring stations in BPDM are lower than the NAAQS; however, the AQMP must be developed for this priority area to ensure ambient air pollutants comply with the NAAQS despite future expansion projects (DEA, 2014).

The next three sections review how the platinum smelters comply with issued AELs.

4.1.1 Anglo American Platinum Mortimer and Waterval Smelters AEL compliance

The Mortimer smelter applied for an exemption to meet SO_2 emission limits that came into force in 2015. To comply with more stringent limits that will come into effect in 2020, the smelter was allowed an opportunity to design appropriate abatement technology and an exemption from compliance with the 2015 emission limits was subsequently granted by the Department of Environmental Affairs (DEA). The interim limits imposed on the Mortimer smelter are, however, lower than what the company has proposed. The company has therefore lodged an appeal with the DEA (Amplats, 2015). The Waterval smelter SO_2 AEL compliance was not mentioned in the Anglo American Platinum sustainable development report of 2015 (Amplats, 2015).

4.1.2 Impala Smelter AEL compliance

The Impala smelter received a new AEL in August 2014 which expires in July 2019. The smelter is fully compliant with its current AEL conditions. It is foreseen that the AEL to be issued to the Impala smelter post-July 2019 is likely to adhere to the 2020 emission standards. Sulphur dioxide levels are monitored at the point source and at ambient air monitoring stations around operations (Implats, 2015).

4.1.3 Lonmin Smelter AEL compliance

The Lonmin smelter's average annual emission in 2015 for SO_2 was 1,820 mg/Nm^3 which is below the year 2015 emission standard of 2 500 mg/Nm^3 (feed SO_2 > 5% SO_2) or 3 500 mg/Nm^3 (feed SO_2 < 5% SO_2). However, for the smelter to comply with the 2020 SO_2 emission standard of 1 200 mg/Nm^3, Lonmin must invest heavily in pollution abatement equipment. The company is researching appropriate technology that can be implemented to meet the stringent 2020 emission standards. The sulphur fixation plant's annual average SO_2 concentration for the smelter in 2016 was 1 424 mg/Nm^3, which exceeds the 2020 SO_2 emission standard of 1 200 mg/Nm^3. Progress has been made to identify requirements that will enable the company to meet the 2020 emission standards. The company has already indicated that NEMAQA makes provision for emitters to apply for postponement to comply with the emission standards (Lonmin, 2015; Lonmin, 2016).

4.2 Current levels of ambient SO_2 in the Rustenburg region

4.2.1 Boitekong ambient air monitoring station

Data were available for the period from 1 March 2013 to 31 March 2014 (see Figure 4-1). However, data were not recorded from September 2013 to November 2013.

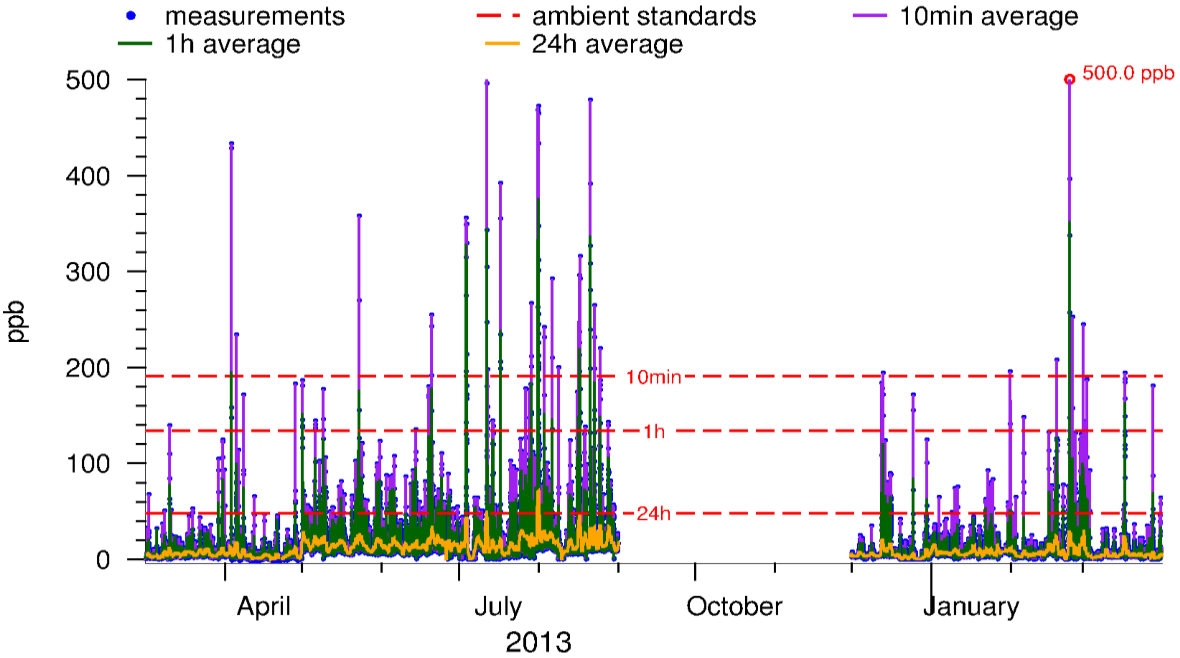

Figure 4-1: Average SO_2 concentration recorded at the Boitekong monitoring station during the period March 2013–March 2014.

The SO_2 10-minute average national standard (191 ppb) was exceeded 23 times compared with the allowable 526 times. The highest concentration recorded was 500 ppb in February 2014. It must be noted that this peak was observed during the period when there was a platinum industry labour strike in Rustenburg and platinum smelters were not operating optimally during that period. The peak can be partly attributed to other sources of SO_2 in the area, such as domestic combustion and biomass burning. However, in July 2013 a concentration of approximately 490 ppb SO_2 was recorded. The 1-hour average national standard (134 ppb) was exceeded 16 times compared with the allowable 88 times. The highest concentration recorded was approximately 380 ppb in July 2013. The SO_2 24-hour average national standard (48 ppb) was exceeded twice compared with the allowable four times. The highest concentration recorded was approximately 70 ppb in August 2013. Sulphur dioxide concentrations monitored at the Boitekong ambient air monitoring station were within the allowable exceedances during the monitoring period. However, unavailability of data from September 2013 to November 2013 may have influenced the number of SO_2 24-hour average allowable exceedances. The ambient air SO_2 concentration at the Boitekong ambient air monitoring station is summarised in Table 4-4.

Table 4-4: Comparison of SO_2 concentrations recorded at the Boitekong, Marikana and Tlhabane ambient air monitoring stations with the South African ambient air quality standards.

	SO_2 10-minute average	**SO_2 1-hour average**	**SO_2 24-hour average**
Unit	ppb		
National Ambient Air Quality Standard	191	134	48
Exceedance frequency allowed (p.a.)	526	88	4
Boitekong frequency of exceedances	23	16	2
Marikana frequency of exceedances	5	4	0
Tlhabane frequency of exceedances	5	4	2

The diurnal pattern of SO_2 levels measured at the Boitekong ambient air monitoring station indicated that the SO_2 concentration (red solid line) increases from approximately 10 ppb at 06:00, attains a peak of approximately 15 ppm at 09:00 and decreases until 14:00 when the concentration stabilises at approximately 8 ppb (Figure 4-2).

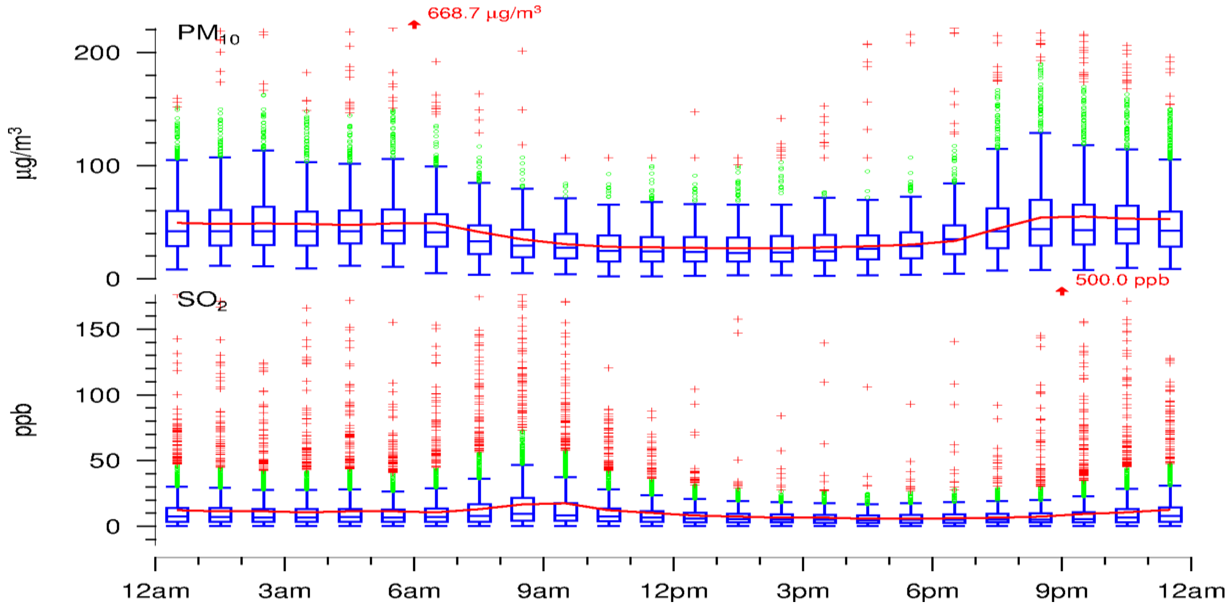

Figure 4-2: Diurnal pattern for SO_2 concentration recorded at the Boitekong monitoring station during the period March 2013–March 2014.

This diurnal pattern is similar to that observed at the Tlhabane ambient air monitoring station (see Figure 4-6).

4.2.2 Marikana ambient air monitoring station

Data were available for the period from 1 May 2013 to 31 March 2014 (see Figure 4-3). However, data were not recorded from September 2013 to November 2013.

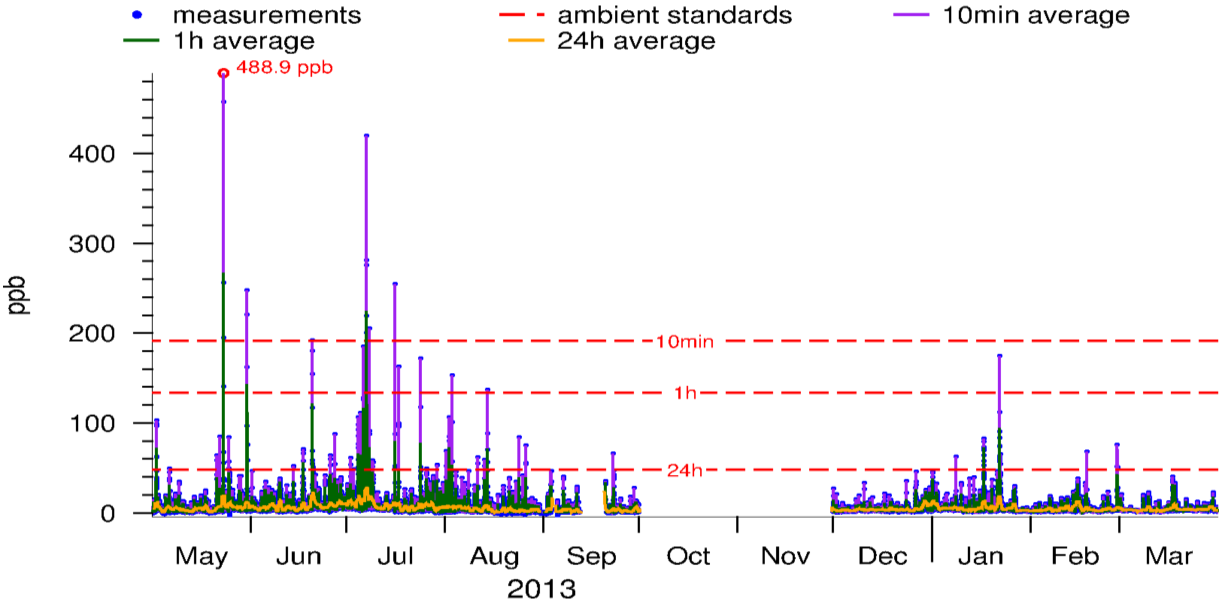

Figure 4-3: Average SO_2 concentrations recorded at the Marikana monitoring station during the period May 2013–March 2014.

The SO_2 10-minute average national standard (191 ppb) was exceeded five times compared with the allowable 526 times. The highest concentration recorded was 488.9 ppb in May 2013. The SO_2 1-hour average national standard (134 ppb) was exceeded four times compared with the allowable 88 times. The highest concentration recorded was approximately 260 ppb in May 2013. The SO_2 24-hour average national standard (48 ppb) was not exceeded during the monitoring period. The SO_2 levels monitored at the Marikana ambient air monitoring station were within the allowable exceedances during the monitoring period. However, the unavailability of data from March 2013 to April 2013 and again from October 2013 to November 2013 may have influenced the number of SO_2 24-hour average allowable exceedances. The SO_2 concentration at the Marikana ambient air monitoring station is summarised in Table 4-4.

The diurnal pattern indicated that the SO_2 concentration increases from approximately 4 ppb at 07:00, attains a peak of approximately 8 ppm between 10:00 and 11:00, and decreases slightly until 17:00 when the concentration stabilises at approximately 6 ppb (Figure 4-4).

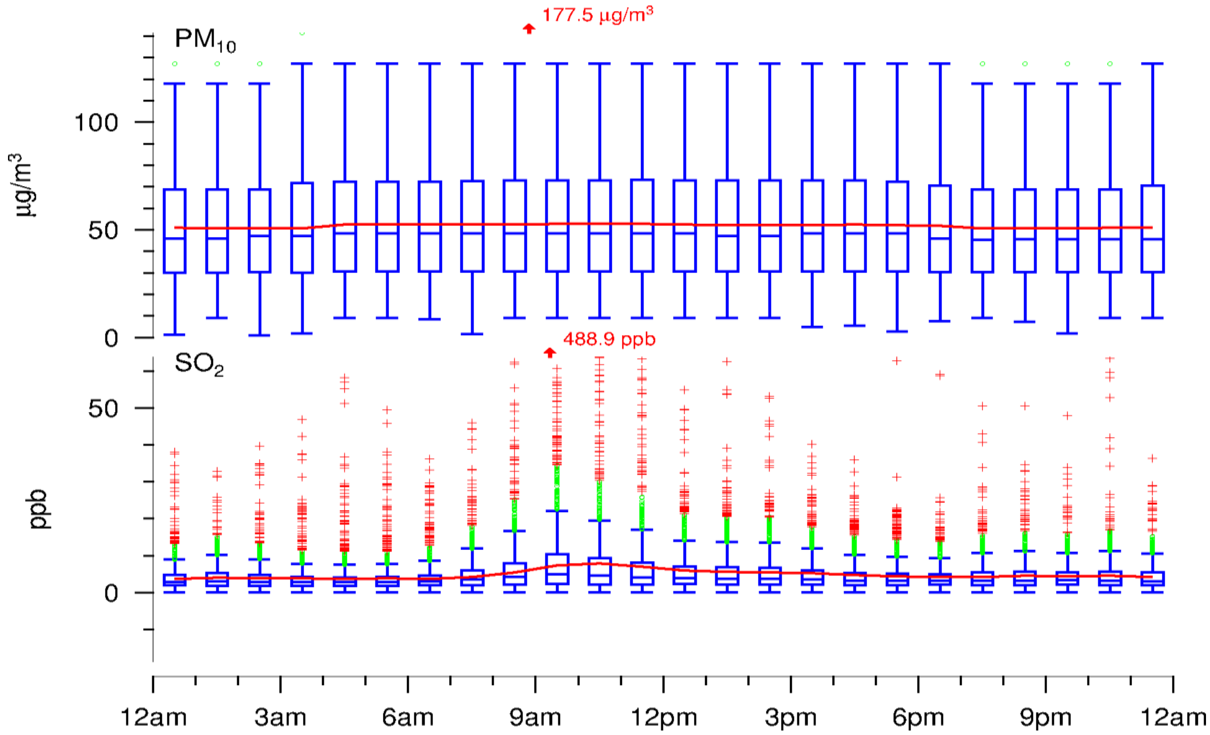

Figure 4-4: Diurnal pattern for SO_2 concentration recorded at the Marikana monitoring station during the period May 2013–March 2014.

This diurnal pattern differs from that observed at the Tlhabane and Boitekong ambient air monitoring stations, where the SO_2 concentration between 06:00 and 12:00 is similar and a peak is attained at about 09:00.

4.2.3 Tlhabane ambient air monitoring station

Data were available for the period from 1 March 2013 to 31 March 2014 (see Figure 4-5). Data were not recorded from October 2013 to November 2013. It must be noted that from January 2014 to March 2014 there was a platinum industry labour strike in Rustenburg, resulting in a substantial scaling down of production; therefore, a significant reduction in platinum smelter emissions in the area during that period can be expected.

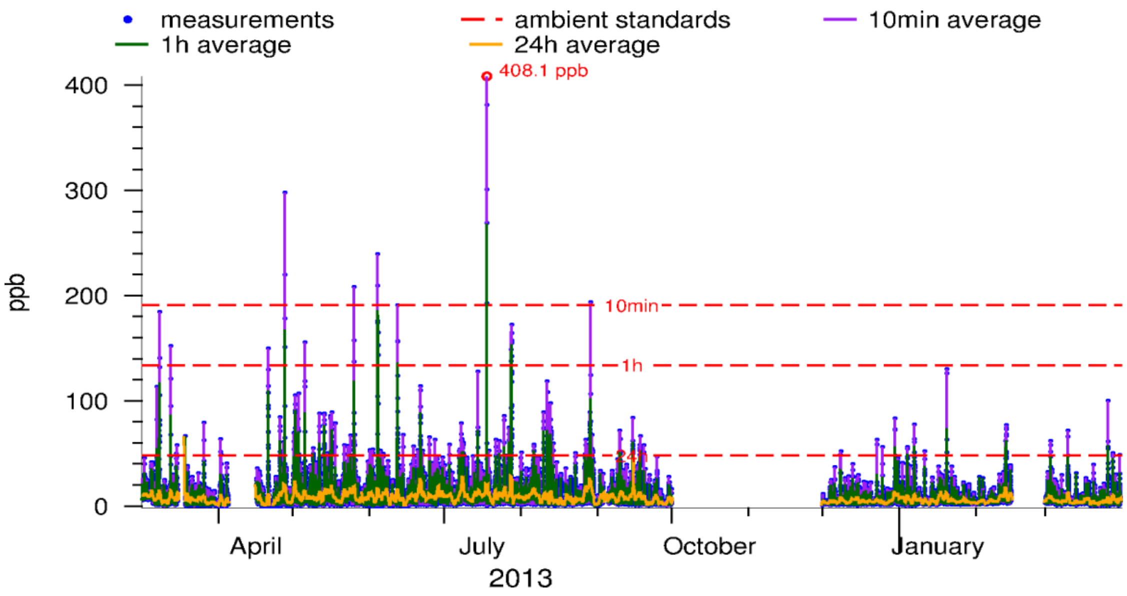

Figure 4-5: Average SO_2 concentrations recorded at the Tlhabane monitoring station during the period March 2013–March 2014.

The SO_2 10-minute average national standard (191 ppb) was exceeded five times compared with the allowable 526 times. The highest concentration recorded was 408 ppb in July 2013. The SO_2 1-hour average national standard (134 ppb) was exceeded four times compared with the allowable 88 times. The highest concentration recorded was approximately 270 ppb in July 2013. The SO_2 24-hour average national standard (48 ppb) was exceeded twice compared with the allowable four times. The highest concentration recorded was approximately 70 ppb in March 2013. The SO_2 levels monitored at the Tlhabane ambient air monitoring station were within the allowable exceedances during the monitoring period. However, unavailability of data during October 2013 and November 2013 may have influenced the number of the SO_2 24-hour average allowable exceedances. The SO_2 concentration at the Tlhabane ambient air monitoring station is summarised in Table 4-4.

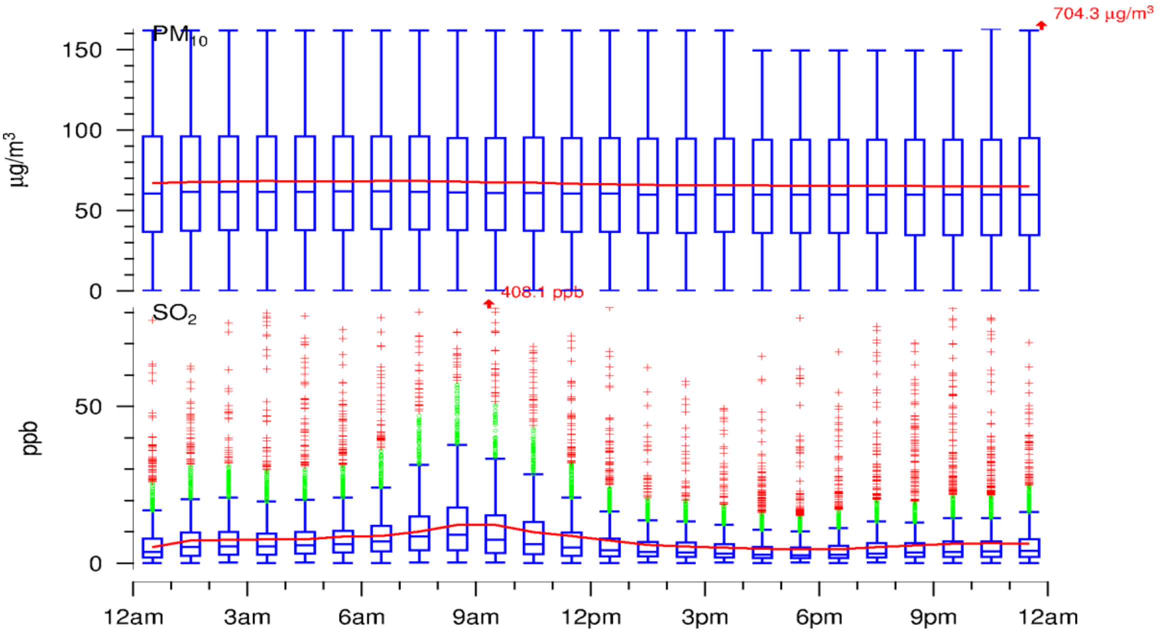

Figure 4-6: Diurnal pattern for SO_2 concentration recorded at the Tlhabane monitoring station during the period March 2013–March 2014.

The diurnal pattern indicated that the SO_2 concentration increases from approximately 10 ppb at 06:00, attains a peak of approximately 15 ppm at 09:00, and decreases until 15:00 when the concentration stabilises at approximately 8 ppb (Figure 4-6).

4.2.4 Anglo American Platinum ambient air stations

Anglo American Platinum monitors ambient SO_2 levels at eight ambient air monitoring stations in the Rustenburg area (Figure 4-7, Table 4-2). The Bergsig monitoring station, which is situated in the residential area of Rustenburg, and the Wonderkop monitoring station situated near Marikana had low data coverage due to lightning strike and vandalism. A tower plant failure at the Waterval smelter resulted in high SO_2 emissions in March, July and August 2013; however, the emissions were not higher than the annual allowable exceedances. The Mfidikwe monitoring station, which is situated in a residential area in close proximity to the Waterval smelter, had four exceedances above the daily SO_2 limit of 125 µg/m^3. During the Mfidikwe exceedances, the wind direction was generally south-westerly to north-westerly, implying that the likely source of the SO_2 was the Waterval smelter. These exceedances equal the number of annual allowable exceedances. No SO_2 level exceedances were reported above the annual allowable exceedances (Amplats, 2013).

Table 4-5: Anglo American Platinum Rustenburg ambient air quality monitoring statistics for the period 1 January to 31 December 2013

Station name	SO_2 data captured (%)	Number of SO_2 exceedances above 10-min average ambient air limit of 500 µg/m^3 [allowed exceedances ≤ 526]	Number of SO_2 exceedances above hourly average ambient air limit of 350 µg/m^3 [allowed exceedances ≤ 88]	Number of SO_2 exceedances above daily average ambient air limit of 125 µg/m^3 [allowed exceedances ≤ 4]
Bergsig[3]	77.1	4	1	0
Brakspruit	90.7	89	4	1
Hex	75.7	31	4	0
Klipfontein	70.9	24	6	0
Mfidikwe	91.5	201	42	4
Paardekraal	82.3	48	15	1
Waterval	91.3	81	14	0
Wonderkop[4]	90.1	2	1	0

(Source: Amplats, 2013).

The data from ambient air monitoring stations used in dispersion modelling (Table 4-1) and data from the Anglo American Platinum monitoring stations (Table 4-2) indicated that were no SO_2 exceedances above the allowable frequencies. Therefore, the data from the eight Anglo American Platinum ambient air monitoring stations validate the modelled data from the three ambient air monitoring stations used in this research.

[3] The Bergsig monitoring station was struck by lightning during December 2012 and recommissioned during October 2013

[4] The Wonderkop monitoring station was vandalised on 25 January 2013 and recommissioned on 21 October 2013

4.2.5 Ambient air monitoring in the Rustenburg area

Parts of the ambient air monitoring network in the Rustenburg area are depicted in Figure 4-7. The monitoring network includes three stations administered by the Rustenburg Local Municipality (stations used for this research), two by the North West Provincial Government, three stations by Impala Platinum, eight by Anglo American Platinum, two by Lonmin Platinum and one by Glencore Rustenburg. There are additional ambient air stations not depicted in Figure 4-7 (see BEUP, 2015).

The eight Anglo American Platinum Rustenburg ambient air monitoring stations are listed in Table 4-2. Anglo American Platinum also has four ambient air monitoring stations at the Mortimer smelter near Northam (three additional stations were commissioned in November 2013) (Amplats, 2013).

The three Impala Platinum ambient air monitoring stations are situated at Boshoek, Luka and Impala Central Services Offices as depicted in Figure 4-7 (SLR Africa, 2013; BEUP, 2015). Lonmin Platinum has two ambient air monitoring stations situated at BMR and Wonderkop, as depicted in Figure 4-7.

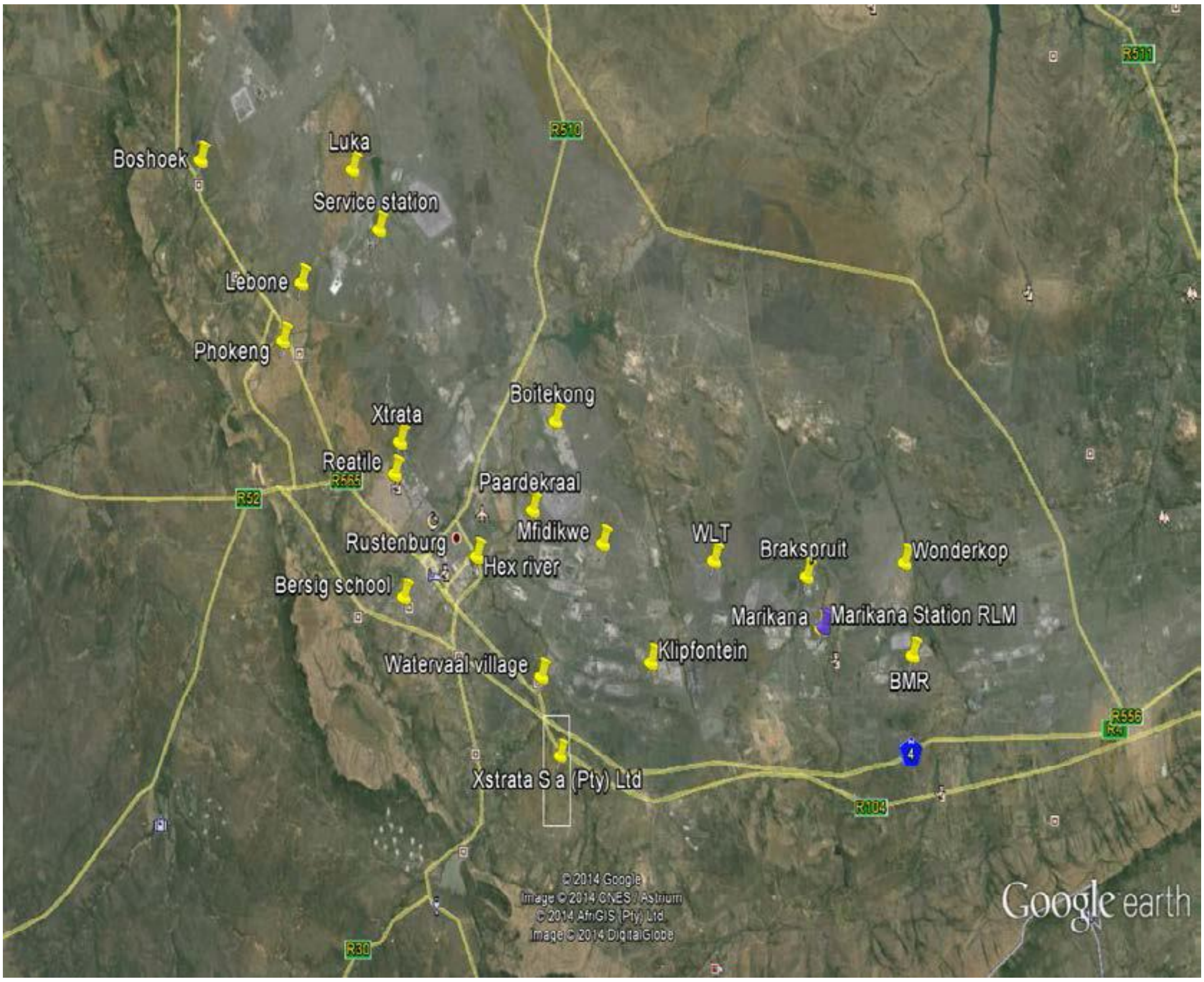

Figure 4-7: Ambient air monitoring stations in the Rustenburg region (BEUP, 2015).

In Taiwan the Environmental Protection Administration (EPA) installed the first air quality monitoring network in 1980. By 2004 there were 72 air monitoring stations. During the same period, the environmental protection bureaux of some county governments installed their own monitoring networks sharing the same objectives as the EPA. The fact that these monitoring stations were not systematically planned and integrated within the national ambient air network led to an ineffective monitoring network (Chen *et al.*, 2006).

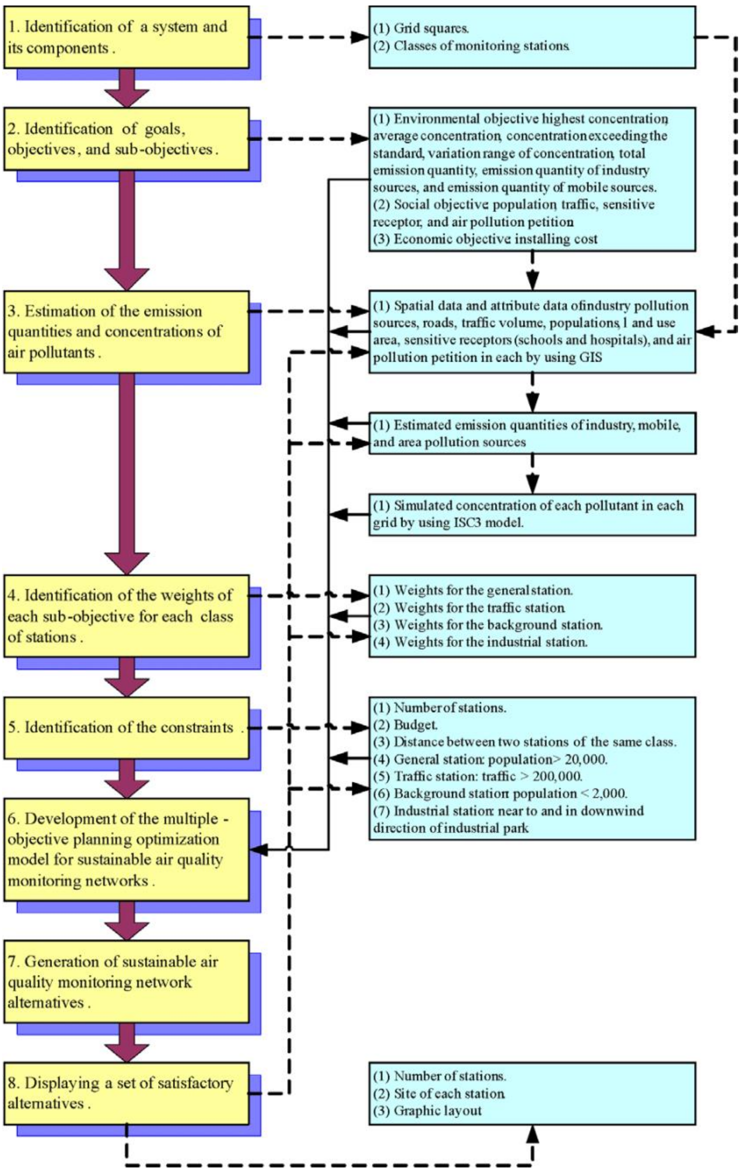

Figure 4-8: The multiple objectives planning procedure for sustainable air quality monitoring networks (Chen *et al.*, 2006).

At least 19 air monitoring stations in the Rustenburg area are not integrated and have been installed by different organisations for different reasons. The symptoms of ineffective monitoring network are evident in the ambient air monitoring network in this area. Chen *et al.* (2006) developed a methodology outlined in Figure 4-8 that can be used to plan air quality monitoring networks. The model incorporates consideration of the environmental, social and economic objectives in order to attain sustainable air quality monitoring networks as required by NAMAQA.

4.3 Platinum smelter impacts on ambient SO_2 levels in the Rustenburg region

Air dispersion modelling was done to determine SO_2 cumulative impacts of the platinum smelters in the Rustenburg area. Predicted 1-hour, 24-hour and annual average SO_2 concentrations are presented in the form of concentration contours in Figures 4-9, 4-10 and 4-11.

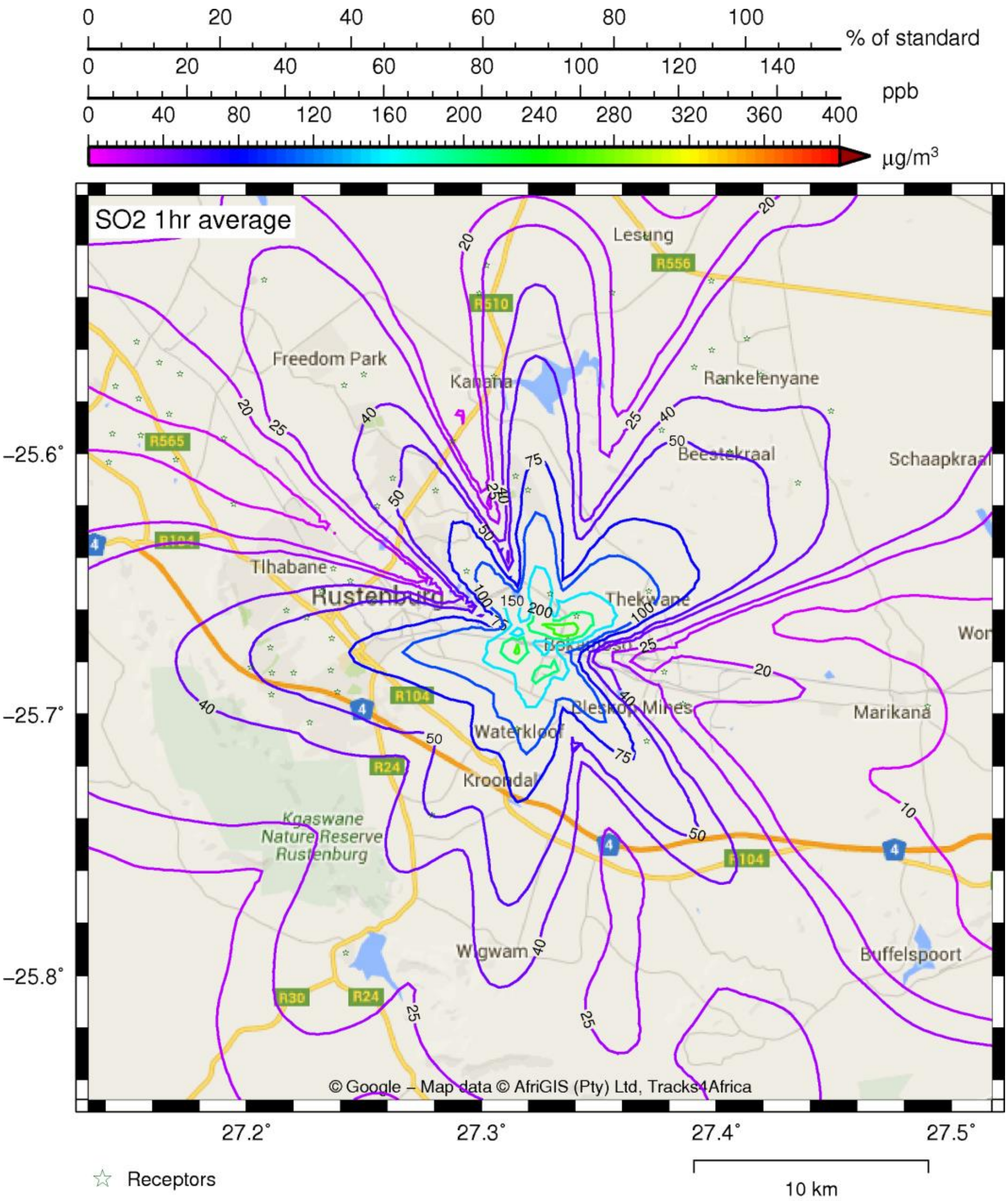

Figure 4-9: Sulphur dioxide 1-hour average concentration due to platinum smelters in the Rustenburg region for 2013 as simulated by the AERMOD dispersion model.

The maximum 1-hour average SO_2 concentration field predicted for the platinum smelters was 200 $\mu g/m^3$ (±80 ppb), which is within the average ambient air limit of

350 µg/m^3. This amount translates to about 60% of the ambient air standard. The area of highest concentration was southeast of Rustenburg and south-west of Thekwane village. This area is in close proximity to the Anglo American Platinum Waterval smelter. The SO_2 concentrations recorded in the Rustenburg region were mostly between 40 and 100 µg/m^3 (see Figure 4-9).

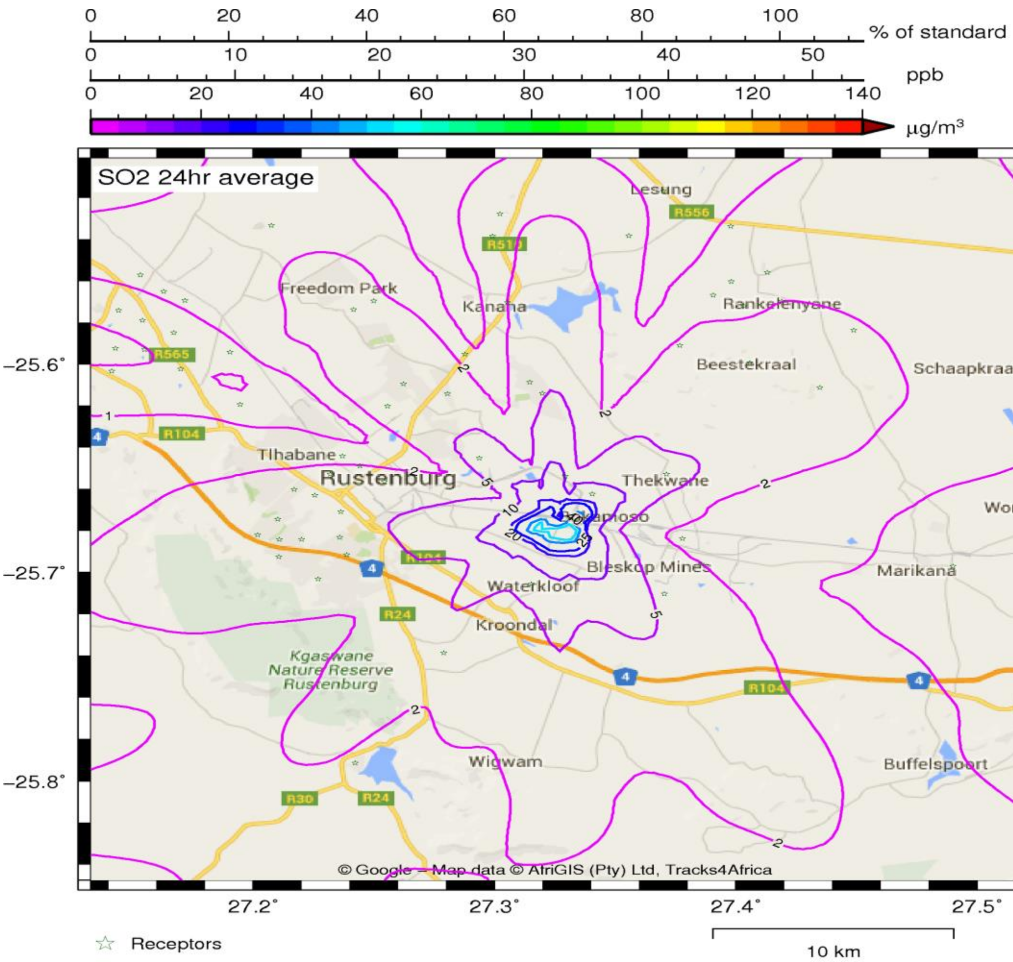

Figure 4-10: Sulphur dioxide 24-hour average concentration due to platinum smelters in the Rustenburg region for 2013 as simulated by the AERMOD dispersion model.

The maximum 24-hour average SO_2 concentration field predicted for the platinum smelters was about 55 µg/m^3 (±22 ppb), which is within the average ambient air limit of 125 µg/m^3. This amount translates to about 45% of the ambient air standard. The area of highest concentration is in close proximity to the Anglo American Platinum Waterval smelter. The SO_2 concentrations recorded in the Rustenburg region were mostly between 2 and 10 µg/m^3 (see Figure 4-10).

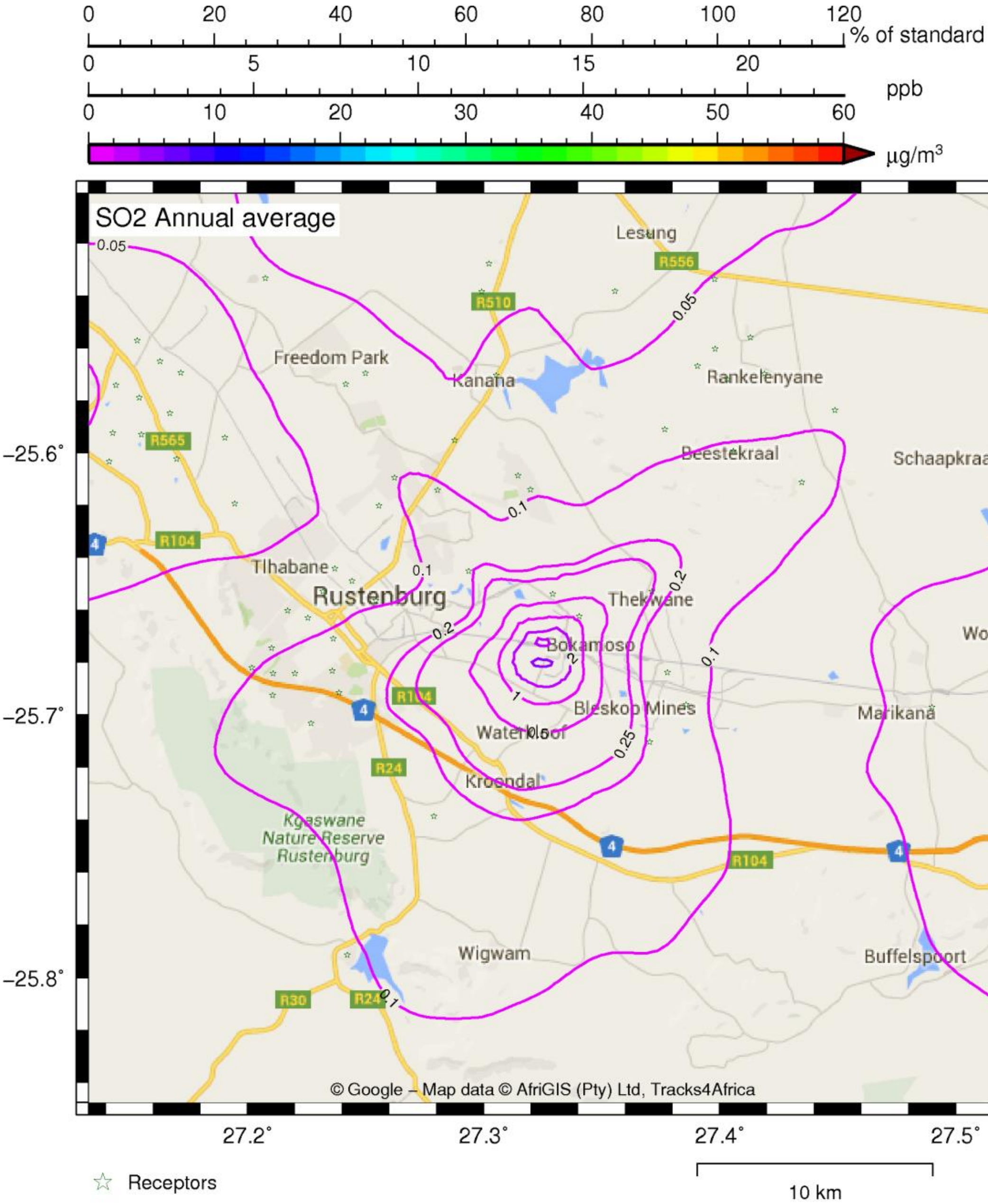

Figure 4-11: Sulphur dioxide annual average concentration due to platinum smelters in the Rustenburg region for 2013 as simulated by the AERMOD dispersion model.

The maximum annual average SO_2 concentration field predicted for the platinum smelters was approximately 6 µg/m^3 (±2.5 ppb), which is within the average ambient air limit of 50 µg/m^3. This amount translates to about 10% of the ambient air standard. The area of highest concentration is in close proximity to the Anglo American Platinum

Waterval smelter. The SO_2 concentrations recorded in the Rustenburg region were mostly between 0.1 and 1 µg/m^3 (see Figure 4-11).

4.4 Concluding remarks on results

The NEMAQA was promulgated to establish reasonable measures to prevent air pollution and degradation of air quality while promoting justifiable economic and social development. With these goals in mind, SO_2 minimum emission standards for point sources and ambient air standards have been published. To prevent air pollution in the Waterberg–Bojanala region due to future expansion projects in the mining industry, the region has been declared a national air quality priority area. Platinum smelters are required to comply with SO_2 point-source emission standards that came into force on 01 April 2015. More stringent SO_2 emission standards will come into effect on 01 April 2020. The industry will be required to invest in appropriate technology to meet future emission standards.

The Mortimer smelter is currently not meeting the 2015 SO_2 emission standards and it is possible that some of the platinum smelters will not meet the more stringent 2020 emission standards. It will be a challenge for old plants to retrofit new technology with old technology in order to meet minimum emission standards. It might not be economically viable to invest in new technology. Many plants might therefore be forced into early closure by 01 April 2020 or apply for postponement to comply with the standards. The unintended outcomes will have negative social impacts due to closure of facilities unable to meet minimum emission standards.

The SO_2 levels monitored at the Boitekong, Marikana and Tlhabane ambient air monitoring stations were within the allowable exceedances during the monitoring period. However, unavailability of data for some months during the monitoring period may have influenced the number of SO_2 24-hour average allowable exceedances. No exceedances above allowable exceedance frequencies were reported at the eight Anglo American Platinum ambient air monitoring stations in the Rustenburg area. This validates the modelled data from the three ambient air monitoring stations used in this research. The diurnal patterns at the three ambient air monitoring stations generally indicated that the SO_2 concentration increases between 06:00 and 11:00, highlighting that domestic combustion may make a significant contribution to ambient SO_2 levels in the morning.

Modelled cumulative impacts of the platinum smelters are well within the allowable 1-hour, 24-hour and annual averages. Ambient air SO_2 levels in the Rustenburg area are not as high as generally perceived and platinum smelters have not compromised ambient air SO_2 levels beyond the legal limit. The ambient air monitoring network conducted by the Rustenburg Local Municipality, North West Provincial Government and mining companies in the Rustenburg area is not integrated, which is a symptom of an ineffective monitoring system.

CHAPTER 5: CONCLUSION

This dissertation aimed to evaluate how SO_2 emissions from platinum smelters in South Africa are regulated. The following objectives assisted to realise the research aim:

(1) Understand the regulatory strategies to manage SO_2 emissions from platinum smelters.

(2) Assess the status of ambient air SO_2 in the Rustenburg region.

(3) Determine the contribution of platinum smelters to ambient air SO_2 levels in the Rustenburg region.

5.1 Understanding of the regulatory strategy to manage SO_2 emissions from platinum smelters

Section 24 of the Constitution of RSA requires the environment to be protected through reasonable legislative measures. Section 2 of the NEMA requires development to be socially, environmentally and economically sustainable. This section further promotes the participation of all interested and affected parties in environmental governance. The NEMAQA was promulgated to provide reasonable measures to prevent degradation of air quality while promoting justifiable economic and social development. Sulphur dioxide minimum emission standards for point sources and ambient air standards were promulgated to give effect to the above-mentioned legislation.

The current and future minimum emission standards are industry-based. Currently, there are listed activities that cannot meet the emissions standards that came into force on 01 April 2015. On 01 April 2020, all of the listed activities in the same industry will be subject to the same minimum emission standards. Some listed activities are likely to be incompatible with the latest abatement technology due to factors such as aging and may be located in areas where ambient air quality is not compromised. Application of the same emission standards for all listed activities in the same industry will result in the lifespan of some listed activities being shortened because it will not be economically viable to install abatement equipment. Negative social impacts are likely to emanate from closure of listed activities due to non-compliance with minimum emission standards. In the spirit of the law, environmental, social and economic factors should be considered when setting emission standards in order to achieve sustainable development.

5.2 Assessment of the status of ambient air SO_2 in the Rustenburg region

Assessment of ambient air SO_2 levels in the Rustenburg area indicated that allowable SO_2 exceedances were not surpassed at the three ambient air monitoring stations chosen for this study. The ambient air SO_2 10-minute average standard of 191 ppb was exceeded 23 times at the Boitekong ambient air monitoring station, and both the Tlhabane and Marikana air monitoring stations had five exceedances compared with the allowable exceedances of 526 times. The ambient air SO_2 1-hour average standard of 134 ppb was exceeded 16 times at the Boitekong monitoring station, and both the Tlhabane and Marikana monitoring stations had four exceedances compared with the allowable exceedances of 88 times. The ambient air SO_2 24-hour average standard of 48 ppb was exceeded twice at both the Boitekong and Tlhabane monitoring stations and no exceedance was recorded at the Marikana monitoring station compared with the allowable exceedances of four times. Based on the ambient air data modelled and reviewed in this research, ambient SO_2 levels in the Rustenburg region are within the ambient air standards.

It must be stated, however, that ambient air data were not available for some months during the monitoring period. It must also be acknowledged that the monitoring stations used as data sources for dispersion modelling were limited to three locations. There may have been pockets of high SO_2 concentrations not captured by the three monitoring stations. Reported data from eight other ambient air monitoring stations owned by Anglo American Platinum in Rustenburg indicated that allowable SO_2 exceedances were not surpassed at those stations. This validates the data from the ambient air monitoring stations used in this study. The locations of the monitoring stations used in this study are in townships where the majority of people live and where the sources of SO_2 have most impact. Therefore, the author has confidence in the fact that there are no SO_2 exceedances above legal requirements in the Rustenburg area.

5.3 Determination of platinum smelters contribution on ambient SO_2 levels in the Rustenburg region.

Sulphur dioxide emissions from platinum smelters in the Rustenburg area were modelled to determine their cumulative impacts in the region. The maximum 1-hour average cumulative concentration was 200 $\mu g/m^3$ (±80 ppb) compared with the ambient air standard of 350 µg/m^3. This amount is approximately 60% of the standard. The maximum 24-hour average was approximately 55 µg/m^3 (±22 ppb) compared with the ambient standard of 125 µg/m^3. This value translates to approximately 45% of the ambient air standard. The maximum annual average was approximately 6 µg/m^3 (±2.5 ppb) compared with the ambient air standard of 50 µg/m^3. This amount translates to about 10% of the ambient air standard. These results indicated that the cumulative impacts of platinum smelters are well within the allowable 1-hour, 24-hour and annual average standards.

Comparing ambient air concentrations (ppb) from monitoring stations with modelled concentrations (ppb) from platinum smelters, it was observed that most of the spikes in concentrations detected by the ambient air monitoring stations correlated with modelled emissions. Therefore, platinum smelters are the major source of SO_2 in the area. There are, however, additional sources of SO_2 as observed in the diurnal patterns.

It must be noted that air dispersion models by their nature are imperfect representations and subject to many potential inaccuracies. Large uncertainties are associated with the emission factors used in air dispersion modelling and the author expects large spatial variability in ambient SO_2 concentrations. However, analysis of data from the ambient air monitoring stations validated the modelled results.

5.4 Overall concluding statement

The current environmental management approach is focused on command and control. More stringent SO_2 emission limits for platinum smelters are not economically and socially justifiable where platinum smelter impacts are well below ambient air standards and ambient air quality is not compromised. In the spirit of NEMA, which promotes participation of interested parties in environmental governance, it is recommended to apply a hybrid approach whereby additional management strategies, such as public disclosure and air quality offsets, are included in the policy. This is likely to increase economic viability and realise social and environmental sustainability.

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