

Modelling source contributions to ambient particulate matter in Kwadela, Mpumalanga

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Dissertation submitted in fulfilment of the requirements for the
degree *Masters of Science in Geography and Environmental
Management* at the North-West University

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Graduation July 2019

22258108

DEDICATION

*This thesis is dedicated to my LORD Jesus Christ,
my dear mother Chantal Burnett and
my grandfather Willem Renier Bosman*

“And there are also many other things which Jesus did, the which, if they should be written every one, I suppose that even the world itself could not contain the books that should be written. Amen.”

John 21:25 (KJV)

PREFACE

This study forms part of an intensive air quality sampling campaign conducted in Kwadela, a small low-income settlement between Bethal and Ermelo, Mpumalanga. The aim of this campaign is to quantify the baseline air quality during summer and winter in a typical low-income, domestic fuel burning community. Ambient air quality standards (AAQS) for particulate matter (PM) are exceeded, confirming that Kwadela has poor air quality. The 99th percentile of the daily averaged PM₁₀ is 96µg/m³, and for PM_{2.5} it is 60µg/m³. Judging from the diurnal profile of PM, with peaks in the mornings and evenings, domestic fuel burning is mainly responsible for these high ambient PM values. This is noteworthy, since Kwadela has fewer than 1 000 households and is located +/- 45km from the nearest industrial source. This also implies that fuel for cooking purposes is enough to raise ambient PM levels to above air quality standards.

This campaign is funded by South African Synthetic Oil Liquid (SASOL). This study was presented in a full paper and an oral presentation at the National Association of Clean Air (NACA) Conference in 2014. I had the privilege of attending two air dispersion modelling courses: American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) and California Puff Model (CALPUFF), one in April 2014 presented by Prof Piketh and Dr Burger, and in August 2014, presented by Lakes Environmental, Prof and Mrs Thé.

The overall aim of this study is to assess the performance of a steady-state Gaussian dispersion model to simulate ambient air quality inside a low-income urban area on the South African Highveld. These areas are home to a significant portion of the South African population. Air quality regulations largely focus on industrial and commercial emitters. In low-income urban areas, a variety of other sources also contribute to air pollution and need to be assessed in order to inform regulatory efforts. This setting is significantly different than the ones where these models were originally developed and with inputs that are typically used.

1. Characterise the ambient PM loading and variability of five low-income urban areas on the South African Highveld.
2. Evaluate the sensitivity of simulated ambient PM to model inputs in Kwadela, Mpumalanga, by comparing different dispersion modelling scenarios.
3. Model and assess the relative contribution of domestic fuel burning, windblown dust, waste burning and surrounding coal-fired industrial sources to ambient PM concentrations in the small low-income settlement of Kwadela, Mpumalanga

The data and methodologies used to accomplish these objectives are discussed in Chapter 3. Objectives 1 and 2 are addressed in Chapter 4, and objective 3 is addressed in Chapter 5.

ACKNOWLEDGEMENTS

I would like to extend my gratitude to the following individuals and organisations for their support during the course of my research: Prof Stuart Piketh for the financial support in everything I needed and more, his input in my research, as well as all the opportunities being able to attend relevant courses and conferences. I feel honoured to have worked under such an esteemed scientist. I am grateful for Dr Roelof Burger for his guidance, encouragement and unending willingness to help in all facets of my research; I am privileged to have benefitted from the expertise of such a respected scientist.

Thank you to the North-West University for giving me the opportunity to do a master's degree and receiving an education of such excellent quality and for all the research support and the facilities made available to use for my research. I hereby acknowledge and thank SASOL and Electricity Supply Commission (ESKOM) for the financial support during my research. Thank you South African Weather Services (SAWS), for the provision of surface and upper air data, and South African Air Quality Information System (SAAQIS) for providing ambient air quality data of the low-income settlements in Gauteng and the Free State and air quality monitoring site locations in South Africa (SA). Thanks to Mr Jasper Dreyer (NWU) for assisting me with the soil classification of the study area and all the detail thereof. Beanca van den Berg, Brigitte Language, and Corne Grové are thanked for helping to collect data during the Kwadela campaign.

Thank you to Jaun van Loggerenberg, for assisting me with some of the maps, having excellent skills in GIS, for his encouragement and companionship, for always being prepared to help during my research and being a very good friend. Thank you to Reinhardt Hauptfleisch for his support and companionship, and being a good friend. Nopasika Mabadi is thanked for her friendship, love, guidance and encouragement. Thank you to my dearest mother for her unending support, inspiration, and love during my research.

ABSTRACT

The rapid growth of urban areas all over the world has deteriorated the quality of the atmosphere and ambient environment. PM with a diameter of $10\mu\text{m}$ and less contributes greatly to critical health impacts. Developing countries such as SA face a great health and environmental problem concerning this matter, as ambient PM levels are particularly high in low-income settlements. At least 64% of SA's population reside in urban environments being affected by these harmful conditions on a daily basis. This evidently requires proper regulations and air quality control in urban environments, especially in low-income settlements, being something most developing countries, including SA, do not have in place. Air dispersion models are important for regulatory purposes and optimising appropriate site-specific abatement strategies that support local environmental policymaking. However, using Gaussian dispersion models as a tool to govern urban air quality has some challenges: variation of ambient air pollution levels in low-income urban areas; uncertainties pertaining to model inputs when simulating intra-urban air quality using a Gaussian dispersion model; the sensitivity of simulated ambient PM to model inputs when modelling intra-urban air pollutants; and uncertainty about the relative contribution of different pollution sources. The overall aim of this study is to assess the performance of a steady-state Gaussian dispersion model to simulate ambient air quality inside a low-income urban area on the South African Highveld. Air quality regulations largely focus on industrial and commercial emitters. In low-income urban areas, a variety of other sources also contribute to air pollution and need to be assessed in order to inform regulatory efforts. This setting is significantly different than the ones where these models were originally developed and with inputs that are typically used. In order to determine this, the challenges previously mentioned will be addressed as follows: firstly, the ambient PM loading and variability of five low-income settlements are characterised; secondly, a summary of the variability of model inputs when simulating intra-urban air quality using a Gaussian dispersion model, AERMOD, is given in the literature review; then, the sensitivity of simulated ambient PM to model inputs in Kwadela, Mpumalanga, is evaluated by comparing different dispersion modelling scenarios; and lastly, the relative contribution of domestic fuel burning, windblown dust, waste burning and surrounding coal-fired industrial sources to PM_{10} in Kwadela is modelled and assessed. The results confirm that local sources do contribute greatly and dominantly to the PM levels of Kwadela, especially windblown dust and domestic fuel burning as opposed to other surrounding pollution sources such as nearby industries. Considering some limitations of the model, the study confirms that a Gaussian dispersion model is an effective tool to use when simulating intra-urban ambient air quality.

Keywords: AERMOD, dispersion modelling, domestic fuel burning, low-income settlements, particulate matter

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LIST OF POLLUTANTS AND ELEMENTS

BaP	Benzo(a)pyrene
BC	Black carbon
Br	Bromine
BTEX	Benzene, toluene, ethylbenzene and xylene
C ₆ H ₆	Benzene
Ca	Calcium
CH ₂ O	Formaldehyde
CH ₄	Methane
CHx	Cyclohexene
Cl	Chlorine
CO	Carbon monoxide
CO ₂	Carbon dioxide
H ₂ S	Hydrogen sulphide
HC	Hydrocarbon
K	Potassium
NO	Nitric oxide
NO ₂	Nitrogen dioxide
NOx	Nitrogen oxides
O ₃	Ozone
P	Phosphorus
Pb	Lead
PM ₁₀	Particulate matter with a diameter of 10 micrometres or less
PM _{2.5}	Particulate matter with a diameter 2.5 micrometres or less
Si	Silicon
SO ₂	Sulphur dioxide
SOx	Sarbanes Oxley
VOC	Volatile organic compounds
Zn	Zinc

ABBREVIATIONS

AAQS	Ambient Air Quality Standards	Geographic Information Systems
ADMS	Atmospheric Dispersion Modelling System	GLC
AERMAP	American Meteorological Society/Environmental Protection Agency Regulatory Model terrain pre-processor	Ground Level Concentration
AERMET	American Meteorological Society/Environmental Protection Agency Regulatory Model Meteorological Processor	HPA
AERMOD	American Meteorological Society/Environmental Protection Agency Regulatory Model	Highveld Priority Area
APPA	Atmospheric Pollution Prevention Act	IEM
CALPUFF	California Puff Model	integrated emission-meteorological models
CE-CERT	Categorical Exclusion – Certificate of Eligibility	MODIS
DEA	Department of Environmental Affairs	Moderate Resolution Imaging Spectroradiometer
EPA	Environmental Protection Agency	NAAQS
FRIDGE	Fund for Research into Industrial Development Growth and Equity	National Ambient Air Quality Standards
GIS		NEM: AQA
		Nation Environmental Management Air Quality Act
		PM
		Particulate Matter
		PRIME
		Plume Rise Model Enhancements
		PS
		Power Station
		SA
		South Africa
		SAAQIS
		South African Air Quality Information System
		SAWS
		South African Weather Service
		UNEP
		United Nations Environment Programme
		WHO
		World Health Organisation

OVERVIEW

In this chapter, the purpose behind the study will be given, followed by the literature review discussing the background of South African air pollution sources and ambient air pollution in low-income settlements, the current South African regulatory instruments managing air pollution, and the practical use of AERMOD as the regulatory dispersion model. Lastly, the study design outlines the problem statement, the research methodology, assumptions and underlying scientific principles of the study.

1. INTRODUCTION

Urban areas and industrial sources have grown rapidly all over the world, transforming the atmospheric environment. In 2015, it was estimated that outdoor air pollution in rural and urban environments results in 3.3 million premature deaths worldwide annually (Lelieveld *et al.*, 2015). PM with a diameter of 10 μ m and less has severe impacts on human health and this is caused by sources such as domestic fuel burning, unpaved roads, poorly maintained vehicles, industries, waste burning and pollution hotspots (Mage *et al.*, 1996; Albalak *et al.*, 1999; Pope III *et al.*, 2002; Pope III *et al.*, 2006; Arku *et al.*, 2008; Cairncross & John, 2004). PM is particularly high in low-income settlements, and local sources contribute significantly to ambient PM levels (Harrison & Yin, 2000; Barnes *et al.*, 2009). This means that intra-urban air pollution is unavoidable for a large part of the world's population, and will adversely affect the health of those inhabiting these settlements. Air pollution sources in the developing world, such as SA and especially in low-income neighbourhoods, are of great concern as the poor air quality in these residential areas affects the people's health negatively on a daily basis (Christopher, 2014; Gierens *et al.*, 2014).

Combustion sources such as domestic fuel burning contribute significantly to urban pollution, as current scientific evidence derived from the North America and Western Europe (NAWE) has indicated and this has been shown to have a spectrum of health effects ranging from eye irritation to death (Fenger, 1999; Cohen *et al.*, 2005; Norman *et al.*, 2007). Emerging evidence has shown the significant correlation between fine particulate exposure and cardiopulmonary morbidity and mortality (Albalak & Keeler, 1999; Brunekreef & Holgate, 2002; Dockery & Pope, 2012). More specific research has also established the correlation between exposure to ambient PM with aerodynamic diameter 2.5 μ m (PM_{2.5}) and human mortality (Thursten *et al.*, 2005 & Bell *et al.*, 2007; Ramsay, 2008; Cairncross *et al.*, 2007).

The urgent requirements are for effective management and proper policy and legislation to be put in place to control ambient air quality in these urban environments, as these low-income communities do not always have access to proper healthcare and schooling to understand the importance of the

effects of air pollution (Liousse *et al.*, 2014; van der Berg, 2014). The current quantification of air pollution's impact in cities in SA is complicated. Air pollution monitoring campaigns focus mainly on extreme air pollution areas, with stations positioned in major urban settlements to monitor population exposure. This makes it complex to calculate total exposure and can be inconsistent as it varies within urban settlements.

Air dispersion models are used as a tool to regulate ambient air quality, but there are some difficulties when modelling these complex intra-urban scenarios. For example, AERMOD was designed to model air pollution concentrations a distance away from the source and not less than 50m from or at exactly the same location as is the case with intra-urban air pollution. In addition, regulatory instruments focus mostly on industries and do not necessarily deal with domestic fuel burning and biomass burning (Hall *et al.*, 2000; Kesarkar *et al.*, 2007; Liousse *et al.*, 1996). Furthermore, the measurement of these sources' contribution to poor air quality using air dispersion models needs some more description and introduces challenges as these conditions are complex, available data is not always sufficient and the models' sensitivity to different input parameters leaves room for error in modelling results. The level of uncertainty and challenges associated with modelling intra-urban ambient air quality should be understood, and guidelines on how to model these intra-urban scenarios need some clarification.

Lastly, the relative contribution of local and surrounding sources to the ambient air quality of urban settlements is not well understood and needs to be assessed (Thurston & Spengler, 1985; Schauer *et al.*, 1996).

1.1 Research objectives

The overall aim of this study is to assess the performance of a steady-state Gaussian dispersion model to simulate ambient air quality inside a low-income urban area on the South African Highveld. These areas are home to a significant portion of the South African population. Air quality regulations largely focus on industrial and commercial emitters. In low-income urban areas, a variety of other sources also contribute to air pollution and need to be assessed in order to inform regulatory efforts. This setting is significantly different than the ones where these models were originally developed and with modelling scenarios that are not typically simulated.

The following research objectives outline the approach of the study:

1. Characterise the ambient PM loading and variability of five low-income urban areas on the South African Highveld.
2. Evaluate the sensitivity of simulated ambient PM to model inputs in Kwadela, Mpumalanga, by comparing different dispersion modelling scenarios.

3. Model and assess the relative contribution of domestic fuel burning, windblown dust, waste burning and surrounding coal-fired industrial sources to ambient PM concentrations in the small low-income settlement of Kwadela, Mpumalanga.

Kwadela is a good case study because of the geographically isolated nature of the settlement. The closest industrial source is more than 45km away. It is expected that sources typical of low-income areas, such as solid fuel burning, waste burning and windblown dust therefore predominantly determine ambient levels of pollution. This provides a unique opportunity to assess the performance of AERMOD, a Gaussian dispersion model, to simulate these sources. Model scenarios are compared against actual monitored data.

The data and methodologies used to accomplish these objectives are discussed in Chapter 2. Objectives 1 and 2 are addressed in Chapter 4, and objective 3 is addressed in Chapter 5.

2. LITERATURE REVIEW

The atmosphere conserves life in various ways and is the earth's largest shared resource. Unfortunately, due to human-driven activities such as industrial development and urban growth, it is placed in great danger (Hunter *et al.*, 2002). Atmospheric degradation in SA is caused by the main pollution sources such as domestic fuel burning, windblown dust, waste burning, industrial sources, biomass burning and transportation. Regulatory dispersion models are used as a tool to simulate air quality and assist in air quality policy-making.

This literature review links to the three objectives of the study: to reduce uncertainty about the relative contribution of different pollution sources, the significant air pollution sources in SA are discussed; to characterise the typical ambient PM concentrations of Kwadela and four other low-income settlements, the air pollution challenge concerning health impacts and air pollution in low-income settlements in SA are discussed; to evaluate the sensitivity of simulated ambient PM to model inputs when modelling intra-urban air pollutants, the current regulatory instruments and model inputs used for managing air quality is explained and outlined.

2.1 Sources of air pollution in South Africa

In this section, the main sources of air pollution in SA will be discussed in detail. These sources include 1) domestic fuel burning, 2) industrial sources and its emissions, with a sub-section focusing more specifically on the South African Highveld in Mpumalanga, also labelled the Highveld Priority Area (HPA), 3) biomass burning, and lastly 4) transportation sources.

2.1.1 Domestic fuel burning in South Africa

Combustion sources such as domestic fuel burning contribute significantly to urban pollution, as current scientific evidence derived from the North America and Western Europe (NAWE) has indicated, and this has been shown to have a spectrum of health effects ranging from eye irritation to death (Fenger, 1999; Cohen *et al.*, 2005). Emerging evidence has shown the significant correlation between fine particulate exposure and cardiopulmonary morbidity and mortality (Albalak & Keeler, 1999; Brunekreef & Holgate, 2002; Dockery & Pope, 2012). More specific research has also established the correlation between exposure to ambient PM with aerodynamic diameter $2.5\mu\text{m}$ (PM_{2.5}) and human mortality (Thursten *et al.*, 2005 & Bell *et al.*, 2007; Ramsay, 2008; Cairncross *et al.*, 2007).

In South Africa, poor air quality in low-income settlements is primarily related to domestic fuel burning as a source of energy (Annegarn *et al.*, 1996; Annegarn, 2006). The following energy carriers are used in South African households: electricity, coal, paraffin, wood, gas and candles. In some cases,

animal dung and waste are burned in poorer residential areas. The burning of paraffin emits pollutants such as carbon monoxide (CO), particulates, polycyclic aromatic hydrocarbons (PAH) and noxious gasses. Large quantities of gaseous and particulate pollutants are emitted from coal burning, such as sulphur dioxide (SO₂), heavy metals and total and respirable particulates (Fund for Research into Industrial Development Growth and Equity (FRIDGE), 2004). Wood burning contributes large amounts of pollutants such as nitrogen oxide (NO), CO, respirable particulates, PAH, particulate benzo(a)pyrene (BaP), formaldehyde (CH₂O) and PM emissions, containing carbon consisting of approximately 50% elemental carbon and 50% condensed hydrocarbon (HC) (Terblanche *et al.*, 1992). Health risks have become a great concern in SA due to the continued and extensive use of coal as a key fuel used for cooking and heating by a large portion of the population (Makonese *et al.*, 2016; Kornelius *et al.*, 2012). In Gauteng and Mpumalanga, coal is readily available and inexpensive; coal consumption cases occur most in these two regions because of the availability and relatively low temperatures during winter seasons. Coal burned for cooking and space heating purposes represents only 2% of coal use, but is responsible for 25% of national particulate emissions (Scorgie, 2012). Wood and paraffin burning is more common in coastal regions, including Cape Town and eThekweni; the use and resultant poisoning of paraffin contributed 0.3% (Cape Town) and 0.5% (eThekweni) to the total direct health cost of SA in 2002 (Scorgie, 2012).

2.1.2 Industrial sources in South Africa

SA is the leading electrical power producer in Africa and also one of the largest coal miners and users in the world (Pretorius *et al.*, 2015). The industry is mostly concentrated in the north-eastern part of the country as the location of industrial resources determines the expanding growth of particular industries (Figure 2-1). The ten industrial hubs of the country can be seen in Figure 2-1 and, in general, manufacturing, mining and power stations make a large contribution to the economic growth of these urban settlements. Ninety percent of South Africa's power generating capacity is based on coal-fired power stations, mostly situated near the Mpumalanga Highveld on the country's major coal deposits (Spalding-Fecher & Matibe, 2003). As a result of the concentration of industrial activity in this region, it is also a primary source of PM, nitrogen oxides (NO_x), SO₂ and carbon dioxide (CO₂) (Pretorius *et al.*, 2015). SA relies mainly on coal to generate electricity and the reason for this is due to the large amount available and the affordability of the resource. Unfortunately, the coal used in SA's power stations is of relatively poor quality as the highest grade of coal is exported. SA built its own nuclear power station in the Western Cape during the 1980s and nuclear power accounts for approximately 6% of electricity generation in the country (DoE, 2018); although it only makes up a small portion of SA's total energy supply, it is very important in an area where there are no coal reserves.

Natural gas produced by SA contributes approximately 1.5% of the national energy supply and, in 2003, approximately 930 000 tonnes of natural gas and 104 860 tonnes of associated condensate were produced and, according to the Department of Energy (DoE), the gas industry is growing rapidly.

Considering petroleum sources, 23 571 million litres of liquid fuels were produced by SA in 2005, approximately 36% of the demand is met by locally produced synthetic fuels made from coal and natural gas and the remaining 64% are made up from crude oil (DoE, 2018).

Access to electricity has been increased tremendously by the Department of Energy since 1994, electrifying 7.2 million households using grid technology and over 143 432 households using off-grid technology, totalling 90.3% access to electricity for lighting (Stats SA, 2016).

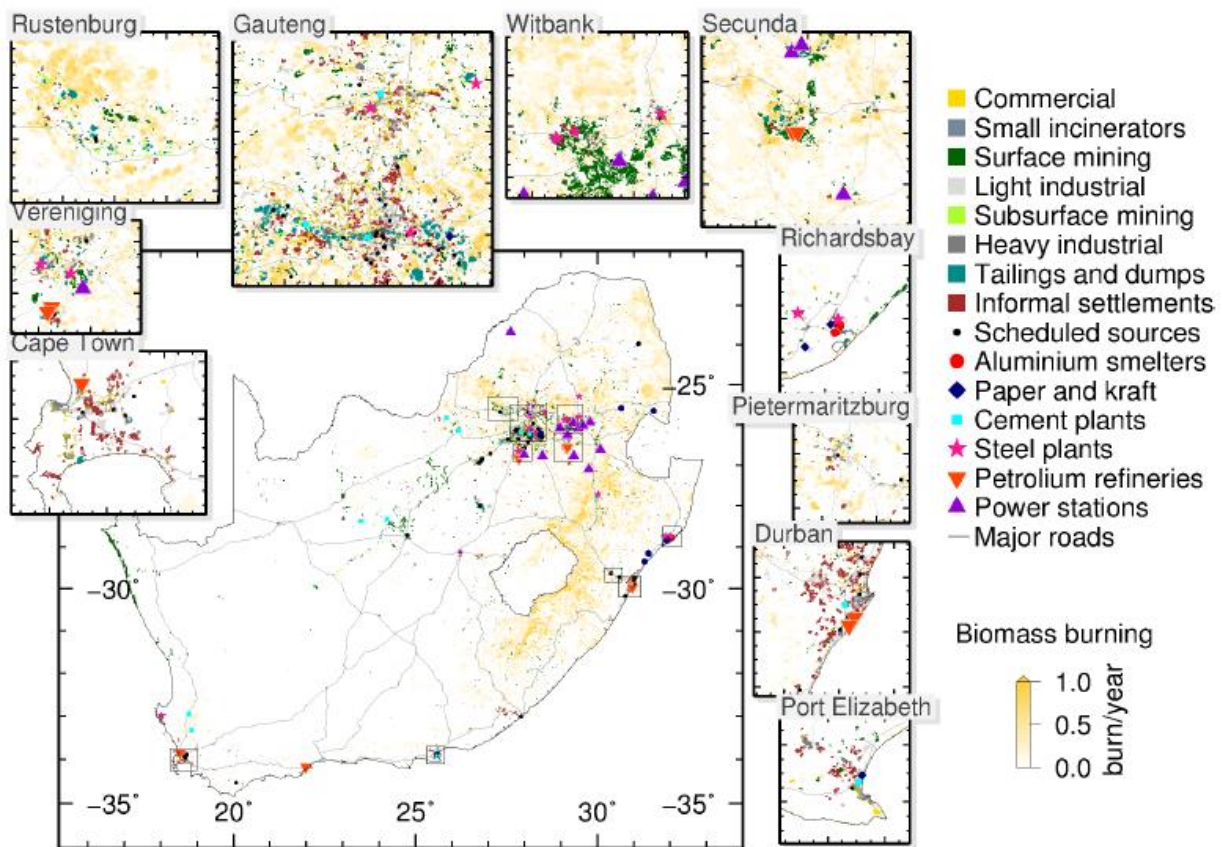


Figure 2-1. Large industries, roads and biomass burning in South Africa, specifically in the urban centres and priority areas (Burger, 2016)

2.1.2.1 The South African Highveld (Mpumalanga)

South Africa's industrial economy has grown to be the largest in Africa (Van Zyl *et al.*, 2014). Five air pollution hotspots have been identified by the Fund for Research into Industrial Development

Growth and Equity, namely eThekweni (Natal), Cape Town (Western Cape), the Cities of Johannesburg and Tshwane (Gauteng), the Vaal Triangle (North West) and the Highveld (Mpumalanga). These areas contribute differently to emissions as the nature and extent of all processes contributing to air pollution vary significantly. Emissions caused by domestic fuel burning, transportation sources, biomass burning and industries and their influence on human health and the environment are impacted by various factors. These determining factors include the location relative to sensitive receptors such as residential areas, the effective height of emissions (taking into account actual height and plume velocity and buoyancy) and temporal variations in emissions (Learner *et al.*, 2009).

The South African Highveld is well known for its various anthropogenic activities such as coal-fired power stations, timber and related industries, petrochemical operations, coal dumps, charcoal producers, brick and stone works, agriculture, metallurgical and mining (primarily coal mines) operations (Lourens *et al.*, 2011). During the dry and cold winters, household coal and wood burning occur more frequently, as well as biomass burning. Previous source apportionment studies have indicated that domestic solid fuel burning contributes 35% to total PM in the Vaal Triangle (Annegarn & Sithole, 1999).

The Mpumalanga Highveld has drawn the attention of air pollution studies for two reasons: firstly, the occurrence of noted elevated air pollution concentrations, and secondly, these various elevated sources of emissions have been connected with long-range transportation of pollutants and the potential of impacting the air quality of nearby and more distant regions (Piketh, 1994). In 2007, the Minister of the Department of Environmental Affairs (DEA) and Tourism under the National Environmental Management Air Quality Act (NEM: AQA) of 2004 declared the Highveld a priority area, which included the eastern and western portions of Gauteng and Mpumalanga, respectively. The HPA does not just have local and regional importance, but is also labelled as an area with some of the highest nitrogen dioxide (NO₂) concentrations in the world indicated by satellite measurements (Lourens *et al.*, 2011).

Considerable health impacts have been acknowledged in the region due to high airborne particulate concentrations. Past studies indicated the existence of elevated particulates, SO₂, O₃, hydrogen sulphide (H₂S) and benzene (C₆H₆) concentrations (Scorgie *et al.*, 2003). The main sources contributing to certain elevated pollutant concentrations are as follows (FRIDGE, 2004): vehicle emissions, domestic coal burning, combustion-related releases and volatile hydrocarbon emissions from the photochemical complex at Secunda make a significant contribution to C₄H₄ in the region; SO₂, particulates, NO_x and O₃ pollutants are caused by power generation, fuel combustion by industries and institutions, domestic fuel burning and vehicle emission sources; emissions from the petrochemical complex in Secunda have been connected with impacts of H₂S; odour impacts are experienced in Johannesburg, given the height at which emissions occur; emissions from waste

incineration may represent a substantial contribution to the emissions of combustion products. As indicated in Figure 2-2, 12 operational coal-fired power stations fall within the defined boundaries of the HPA.

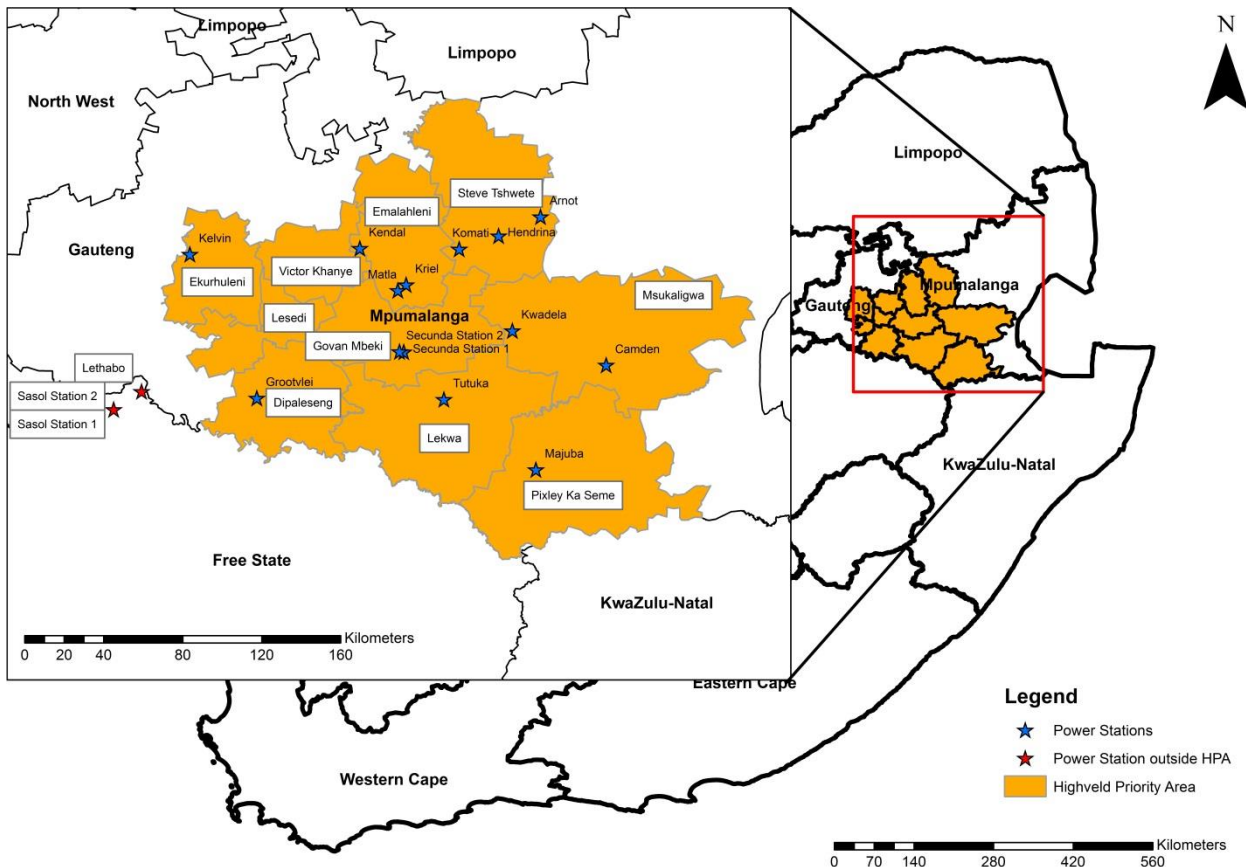


Figure 2-2. The extent of the Mpumalanga Highveld indicating the location of coal-fired power stations located inside and outside the priority area

Coal mines are scattered throughout Mpumalanga with many coal deposits occurring at Witbank. Metal-related industries such as Transalloys and Columbus Steel are located in the Witbank/Middelburg area. The Sasol Synfuels factories are situated in Secunda and industries manufacturing bricks, stone and cement are focused in Nelspruit and the Witbank/Middelburg region. The main activities resulting in atmospheric emissions, related to forestry and timber, include burning of waste wood or timber, fire breaks by the forest industry and forest slash. Domestic fuel burning has been identified as a significant pollutant contributing to poor air quality causing health impacts. As the Mpumalanga Highveld consists of large agricultural areas, its conserved land and wildlife areas should also be considered when biomass burning emissions are calculated as it has been acknowledged as another important source of atmospheric particulates and gases.

2.1.3 Biomass burning in South Africa

Biomass burning is known to be the biggest contributor to primary carbonaceous aerosol particles and reactive trace gases into the atmosphere (Vakkari *et al.*, 2014; Lioussse *et al.*, 2010). Biomass burning in SA can be both natural or anthropogenic. Natural 'veld fires' are almost impossible to control and cannot be eliminated as a source of air pollution. Lightning stands as the primary natural cause of vegetation fires; however, 70 to 90% of all vegetation fires are estimated to be man-made (Helas & Pienaar, 1996). Man-made fires are primarily associated with: agricultural reasons, adjustment of land use, preparation for hunting season and negligence. Various agricultural reasons include: a) removing inedible growth left over from previous seasons, b) stimulation of growth in seasons when feed is not sufficient in the veld, c) to reduce parasites, and d) to keep the field clean of all unwanted plants (Streets *et al.*, 2003; Koppman *et al.*, 2005). As biomass burning is a partial combustion process, it emits CO, methane (CH₄) and NO₂ (Echalar *et al.*, 1995). The aerosol content of vegetation fires influences the prominence of smoke plumes, and savannah fires are specifically related to emissions of very fine PM (Helas & Pienaar, 1996). Potassium (K), zinc (Zn), phosphorus (P), chlorine (Cl) and bromine (Br) are characteristics identified in emissions of savannah fire aerosols, whereas forest fire emissions contain more silicon (Si) and calcium (Ca) (Echalar *et al.*, 1995). In Figure 2-3, the Moderate Resolution Imaging Spectroradiometer (MODIS) annual burned area is displayed showing that biomass burning occurs mostly in the north-eastern and south-eastern parts of SA. A surface area of 55 531km² (4.63%) was burnt in 2005, making it the largest area burned once a year. A surface area of 815km² (0.07%) is the largest surface area burnt for a second time in one year and occurred in 2011 (Burger, 2016).

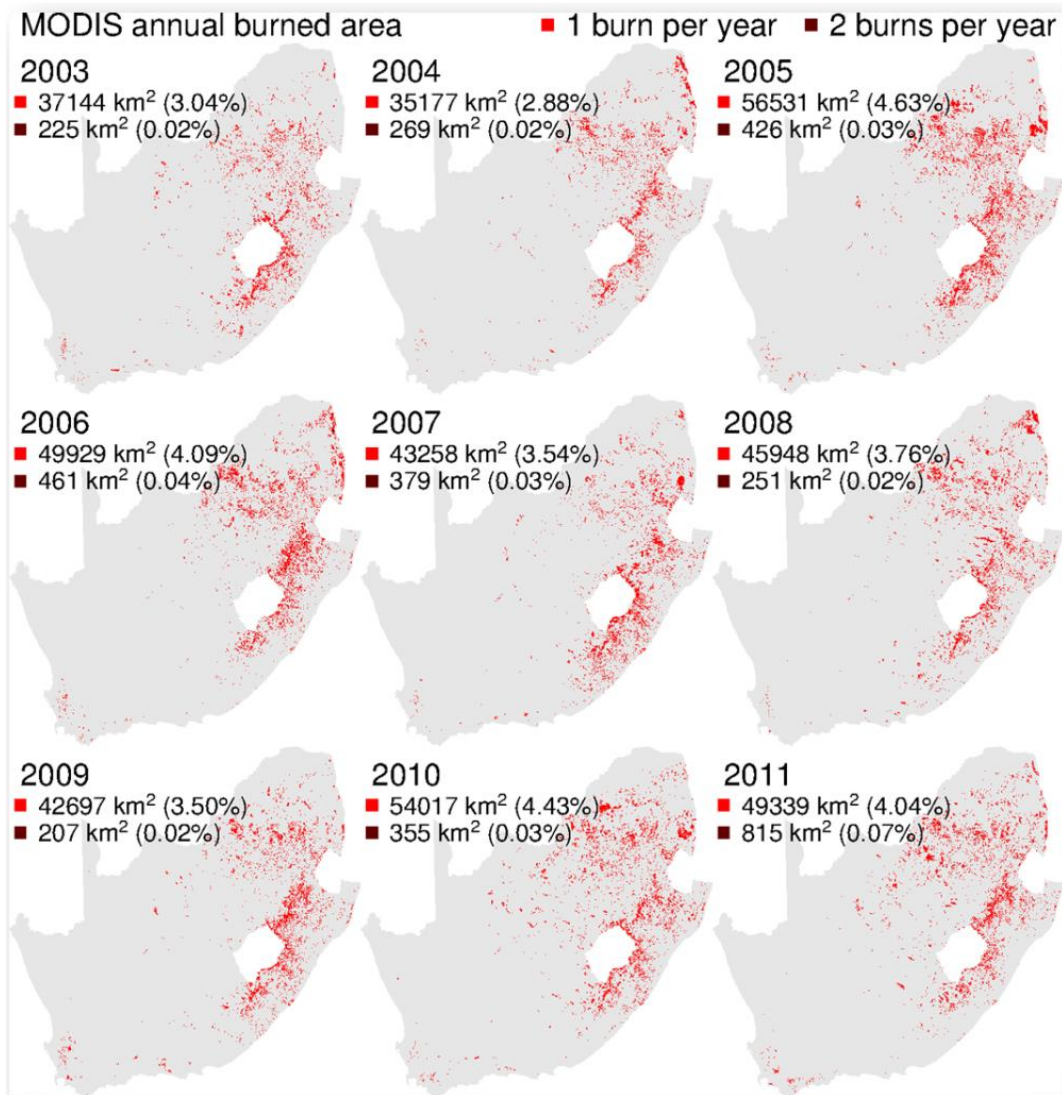


Figure 2-3. MODIS annual burned area in South Africa from 2003-2011 (Burger, 2016)

2.1.4 Transportation sources in South Africa

Transportation sources that add to air pollution include vehicles, railway trains, aircrafts and ships. Certain varying factors, such as travel speeds and distances need to be taken into account when the extent of the emissions from these sources is calculated. Vehicle tailpipe emissions influence the quality of air in close proximity to sensitive zones such as densely populated urban areas. SA has a well-developed road transportation network as seen in Figure 2-4 and it becomes denser closer to sensitive urban areas, contributing more intensely to emissions of urban air pollution and greenhouse gasses (Thambiran & Diab, 2011; Shirinde *et al.*, 2014). Vehicle emissions can be grouped into two groups: primary pollutants and secondary pollutants. Primary pollutants are emitted directly into the atmosphere and can include: CO₂, CO, HC, SO₂, NO_x, particulates and lead (Pb),

whereas secondary pollutants can include NO₂, photochemical oxidants (e.g. ozone), sulphuric acid, sulphates, nitrogen acids and nitrate aerosols (Schwela, 2004).

Dust from unpaved roads is made airborne by passing vehicles and also contributes adversely to the quality of air. This occurs especially in poorer residential areas as roads in poorer communities are often unpaved and not well maintained. This is a near-surface source of dust particles being inhaled by the population causing negative health implications. Road surface moisture controls the suspension of road dust particles; when dust particles are considered precipitation, evaporation and run-off must be taken into account (Omstedt *et al.*, 2005).

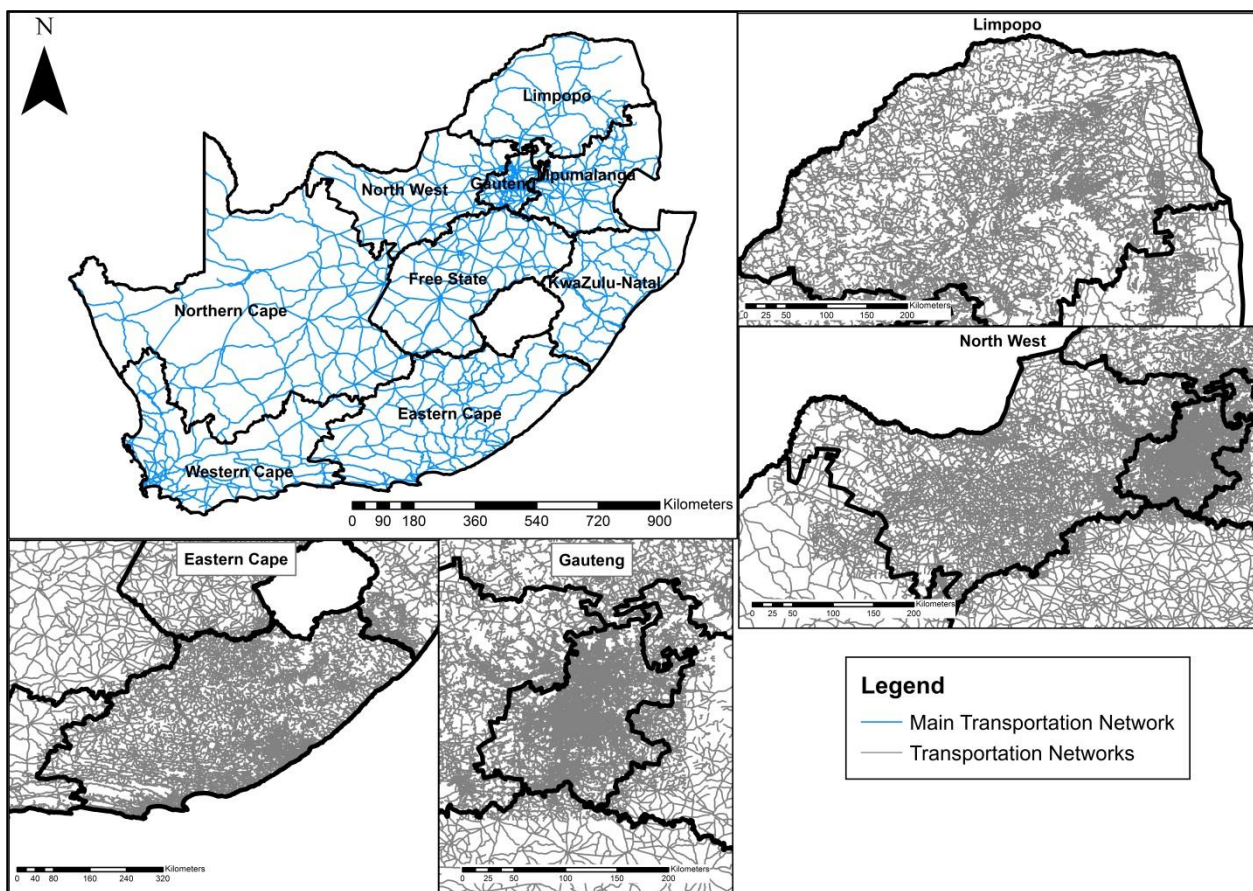


Figure 2-4. Main roads and concentrated transportation pollution hotspots in South Africa

In SA, electric and diesel-powered trains are used primarily in the transportation of bulk materials to and from manufacturing locations (FRIDGE, 2004). Reference may be made to the emission factors for railway traffic emissions estimated by the Department of Energy Engineering at the University of Denmark as this has not been studied locally (Jorgensen & Sorenson, 1997). Aircraft emissions include volatile organic compounds, cyclohexene (CH_x), NO_x, CO and CO₂. After water vapour and CO₂, NO_x represents the largest and CO the second largest emissions associated with aircraft engine emissions (Johnson *et al.*, 1992).

Not much research has been done in SA on shipping as a source of air pollution. SA has five relatively large harbours in Saldana Bay, Cape Town, Port Elizabeth, Durban and Richards Bay, respectively. Fossil fuel combustion by international shipping has been characterised geographically and has indicated that ship sulphur emissions are almost equivalent to natural sulphur change from ocean to atmosphere in many regions (Capaldo *et al.*, 1999).

2.1.5 Emission factors

Emissions produced by sources impacting human health and the environment on a large scale must be quantified and inventoried as it is vital for air quality management (Streets *et al.*, 2003). It is important to calculate emission estimates for the development of emission control strategies, defining applicability of authorising control programmes determining the effects of sources and appropriate mitigation strategies, and various other related applications by a range of users, including national, municipal and local organisations, consultants and industry (National Research Council (NRC), 1991). Source-specific emission tests or continuously monitored emission results are preferred when source emissions are estimated because it provides more accurate results, but this is not always practically possible as individual source data can be unavailable and does not necessarily include the variability of actual emissions over time. Although emission factors have limitations, it is often the most effective method for emission estimates (Garmichael *et al.*, 2003).

An emission factor is defined by the US EPA (1994:1) as “a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant”. These factors can also be described as the weight of the pollutant divided by a unit weight, volume, distance or duration of the activity emitting the pollutant (e.g. kilograms of particulate emitted per mega gram of coal burned) (US EPA, 1994). Such factors enable the estimation of emissions from numerous sources of air pollution and are solely averages of all existing data of adequate quality and are generally assumed to be representative of long-term averages for all facilities in the source classification. It is vital to account for upset periods and routine operations in the device and capture efficiency terms when calculating emissions for a long time period such as one year. Industry emissions can be calculated using the following equation (US EPA AP-42):

$$E = AR \times EF \times (1 - ER/100)$$

Where:

E = emissions

AR = activity rate

EF = emission factor

ER = overall emission reduction efficiency, %

Overall emission reduction efficiency (ER) is further defined as the product of the control device mitigation and the removal efficiency of the control system. Although source-specific tests or continuous emission monitors can determine the actual pollutant contribution from an existing source better than emission factors, the results will be valid only for conditions prevailing at the time of the testing or monitoring (DEA, 2005). To provide the best estimate of longer-term (e. g. annually or typical day) emissions, these conditions should be representative of the source's routine processes. Activity rate (AR) of industries is crucial to take into account with the correct calculations as this determines, for instance, with a coal power plant in SA, the amount of fuel burnt and the variable times it actively emits daily/annually. In most cases, industries emit according to a constant routine and it can be properly monitored or modelled when needed, giving adequate results and ensuring that industries comply with the Minimum National Emission Standards.

Emission limits are set in the National Minimum Emission Standards (promulgated in line with Section 21 of NEM: AQA) and licensing responsibilities are delegated to the local level.

In SA, there are some challenges regarding industrial emissions: fossil fuels are the dominant energy source; SA has limited air quality specialist personnel; some, but not as much as needed, research has been done on the impacts of fossil fuel burning in order to properly address the specific contribution of industrial air pollution, such as impacts from petrochemical industries. Financial implications related to the lessening of the sulphur content in diesel are a challenge.

A great need exists for a central location for data storage of all exposure, demographic and health data and for local government air quality monitoring systems to correspond to ensure compatibility.

There are two information systems to consider when working with emissions in SA, namely the Atmospheric Emission Licensing Module of the SAAQIS and the South African National Atmospheric Emissions Inventory System (NAEIS). The Atmospheric Emission Licencing Module of the SAAQIS provides information and resources related to atmospheric emission sources listed in terms of section 21 of the National Environmental Management Air Quality Act, Act No. 39 of 2004 (NEM: AQA). The NAEIS is the reporting module of SAAQIS into which license holders report their emissions on an annual basis. The NAEIS strives to provide all stakeholders with relevant, up-to-date and correct information on SA's emission profile in order to promote educated decision-making.

2.2 The air pollution challenge concerning health impacts in South Africa

In SA, low-income settlements represent the largest challenge in terms of exposure of the population to PM (Van den Berg *et al.*, 2014). This is not unique to SA and is a common challenge around the globe. The highest burden of disease resulting from exposure to PM occurs in communities caused by the essential use of domestic fuel combustion as a primary source of energy (The World Bank, 2016; Lelieveld *et al.*, 2015; Butt *et al.*, 2015; Kornelius *et al.*, 2012). In South Africa, 45.5% of the population represent the low-income class (based on data collected in 2011). It is estimated that

approximately half of these people are using these low-cost fuels as a primary source of energy. The burning of fuels in the domestic setting contributes significantly to PM levels being breathed in by the exposed population on a daily basis (SSA, 2014). The bulk of the local energy supply (local generation and imports) is obtained from coal (73.59%) and the remaining supply comes from sources such as biofuels and waste (10.49%), crude oil (10.11%), and other (5.79% (DoE, 2012). Research has clearly shown that domestic fuel burning has a substantial impact on health compared to other air pollution sources in SA (Pauw *et al.*, 2008; Kornelius *et al.*, 2012). In urban and industrialised areas such as Rustenburg and Sasolburg, domestic sources were responsible for 69% of total health impacts as a result of ambient air pollution (FRIDGE, 2004; Norman *et al.*, 2007). Domestic use of dirty fuels was found to be responsible for 100% of all indoor PM (Bizzo *et al.*, 2004; Lloyd, 2006; Norman *et al.*, 2007).

As this country has various mining activities, especially coal mines, coal is used as one of the primary fuels. As a result of domestic coal consumption, the outdoor air quality compliance levels are exceeded by 20 to 40% of annual days across the country (Worobiec, 2011).

Gases and particulates being produced during domestic burning leads to 'smog' and occurs more frequently in colder regions during winter, especially among the low socio-economic parts of the population (Barnes *et al.*, 2009). Urban centres' air pollution levels and the cause thereof may vary according to the neighbourhood's socio-demographic characteristics, its location and meteorological factors (Arku *et al.*, 2008). Cultural practices serve as a deeper reason why this type of burning for heating and cooking is preferred by some African citizens: they have been taught this way for many generations and tend to hold on to their traditional beliefs even if it has definite harmful health impacts (Bruce, 2000). Families prefer traditional stoves throughout the winter because it is multi-functional as it gives heat, warm water and cooks food at the same time. Traditional iron stoves, welded stoves or braziers typically make use of coal and wood combustion, and these stoves transfer heat slowly requiring longer burning periods contributing even more to poor indoor and ambient air quality (van den Berg, 2014). Stoves are passed on to family members, which means that poorly ventilated stoves and chimneys remain in use (Balmer, 2007).

2.2.1 Air pollution in low-income settlements in South Africa

Low-income settlements are found especially in developing countries and in these residential areas various human activities contribute to air pollution. PM contributes greatly to poor air quality in low-income settlements and in many parts of the world (Arku *et al.*, 2008; El-Fadel & Massoud, 2000; Cohen *et al.*, 2005). PM is a widespread air pollutant, containing a combination of solid and liquid particles suspended in the air (WHO, 2013). Together with transportation, biomass burning and industrialised sources, domestic fuel burning contributes greatly to atmospheric PM as more than three quarters of this continent's population uses it for crucial daily activities such as cooking and

heating (Harrison & Yin, 2000; Bailis *et al.*, 2005; Kornelius *et al.*, 2013). Apart from PM, these ineffective combustion methods and low-income settlement circumstances also result in other pollutants such as free radicals, HC, oxygenated organics, chlorinated organics, SO₂, CO, NO₂ and dust from unpaved roads and unused open spaces (Dab *et al.*, 1996; Boman *et al.*, 2003; Zhang & Smith, 2007; Naeher *et al.*, 2007).

Environmental policies have been increasingly informed using this evidence, resulting in the impact of air pollution on public health to become a critical component in policy discussions; unfortunately, regulatory instruments often focus on industrial facilities and do not give issues such as domestic fuel burning the needed attention (Lvovsky *et al.*, 2000). Regulating industries is less complex as emitting time schedules can give definite amounts of stack gas pollution, thorough information on how much of what is being used is available and exact restrictions are set in place to control specific pollutants. Air quality management techniques such as fuel changes, emission control technologies, industrial restructuring, and modernisation of transport systems are being implemented around the world. The incorporation of these techniques into urban settlements is vital to ensure and improve air quality. Urban air pollution is regulated by air quality standards in most of the industrialised parts of the world, since, in 1974, the World Health Organisation (WHO) and United Nations Environment Programme (UNEP) have, within the Global Environment Monitoring System, collaborated on a project to monitor urban air quality, called the GEMS/AIR (Fenger, 2009).

A few studies have been done on air pollution sources, levels and variations focusing specifically on the developing world, especially focusing on low-income neighbourhoods (Engelbrecht *et al.*, 2001; Saksena *et al.*, 2003; Chowdhury, 2004; Etyemezian *et al.*, 2005; Jackson, 2005; Zheng *et al.*, 2005; Josipovic *et al.*, 2012; Scorgie *et al.*, 2012; Kornelius *et al.*, 2012; Kornelius *et al.*, 2013). Other studies done on intra-urban air pollution, specifically focusing on domestic fuel burning, include Cooper (2015), Zhao and Sun (2012), Xu *et al.* (2010), and Boman *et al.* (2003), Engelbrecht *et al.* (2000) and they all stress the great need for effective management as it causes immense health impacts on a daily basis (Mage *et al.*, 1996; Arku *et al.*, 2008). It is critical to understand why domestic fuel burning has greater potential for health impacts even when being a fraction of, for example, industrial emissions: 1) fuel burning in houses occurs at ground level, being low-level emissions caused by many sources; 2) the added effect of meteorological conditions at night over the Highveld makes these conditions even worse (Freiman & Piketh, 2002) as burning peak times occur in early mornings and evenings and pollution stagnates in those hours due to limited mixing depths and stable atmospheric conditions (FRIDGE, 2004); and 3) these cooking devices are of poor quality with insufficient ventilation; the pollution is emitted in a limited space as it is mainly burned indoors resulting in higher concentrated emission levels. During winter seasons, burning rates also increase due to a greater need for space heating. Not all residents use the same fuel or the same coal stoves, as income, fuel availability and the family needs differ from one house to another, but wood and coal

are mostly used. This polluted air is being inhaled by a large group of the population, especially woman, and the more vulnerable part of the population, children and the elderly, often staying at home.

Various epidemiological studies indicate that air pollutants, especially respirable PM with an aerodynamic diameter of less than 10 μ m (PM₁₀) can have adverse effects on human health (Seaton *et al.*, 1995; Pope *et al.*, 2002; Yuan & Dong, 2006; Hou *et al.*, 2010; Aurela *et al.*, 2016). Particulates can provoke both acute and chronic bronchitis, asthma, pneumonia, lung cancer and other respiratory and cardiac illnesses and are predominantly harmful to elderly people and children (De Koning *et al.*, 1985; Albalak, 1999; Pope *et al.*, 2006; Brook *et al.*, 2010; WHO, 2013). Numerous studies have also found a significant association between SO₂ and daily mortality, respiratory symptoms and asthma (Schwartz *et al.*, 1993; Xu *et al.*, 1994; Harré *et al.*, 1997; Sheppard *et al.*, 1999; Hales *et al.*, 2000; Yu *et al.*, 2000; Xu *et al.*, 2000).

2.2.2 Geographic variability of air pollution in low-income settlements in South Africa

As mentioned previously, PM is the air pollutant with the highest level of health impacts in low-income settlements in South Africa. In many townships around the country, the PM concentrations in both the PM₁₀ and PM_{2.5} fractions frequently exceed the National Ambient Air Quality Standards (NAAQS) (Engelbrecht *et al.*, 2001). If the population is denser, poverty is more common; more domestic use of dirty fuels occurs leading to more PM in the atmosphere as a result of air pollution. Even though population density plays a significant role in the geographic variability of PM, one must not underestimate the implication of the fuel resource availability for that location and how it is burnt. In SA, various fuel types are used such as coal, wood, paraffin or dung. The fuel type being used depends on certain factors such as availability, income, dwelling type, population characteristics and seasonal variations and meteorology (van den Berg, 2014).

Figure 2-5 displays the geographic locations of SA's coal mines, which are predominantly concentrated on the Mpumalanga Highveld, Limpopo and KwaZulu-Natal, and in these provinces, coal is the most commonly used fuel. Wood, on the other hand, is available over the largest extent of the country and in provinces without coal mines, used more often (Figure 2-6), but dependent on biomes with woody vegetation (Scorgie, 2012). Paraffin is mostly used in Gauteng, but not as frequently as wood or coal (van den Berg, 2014).

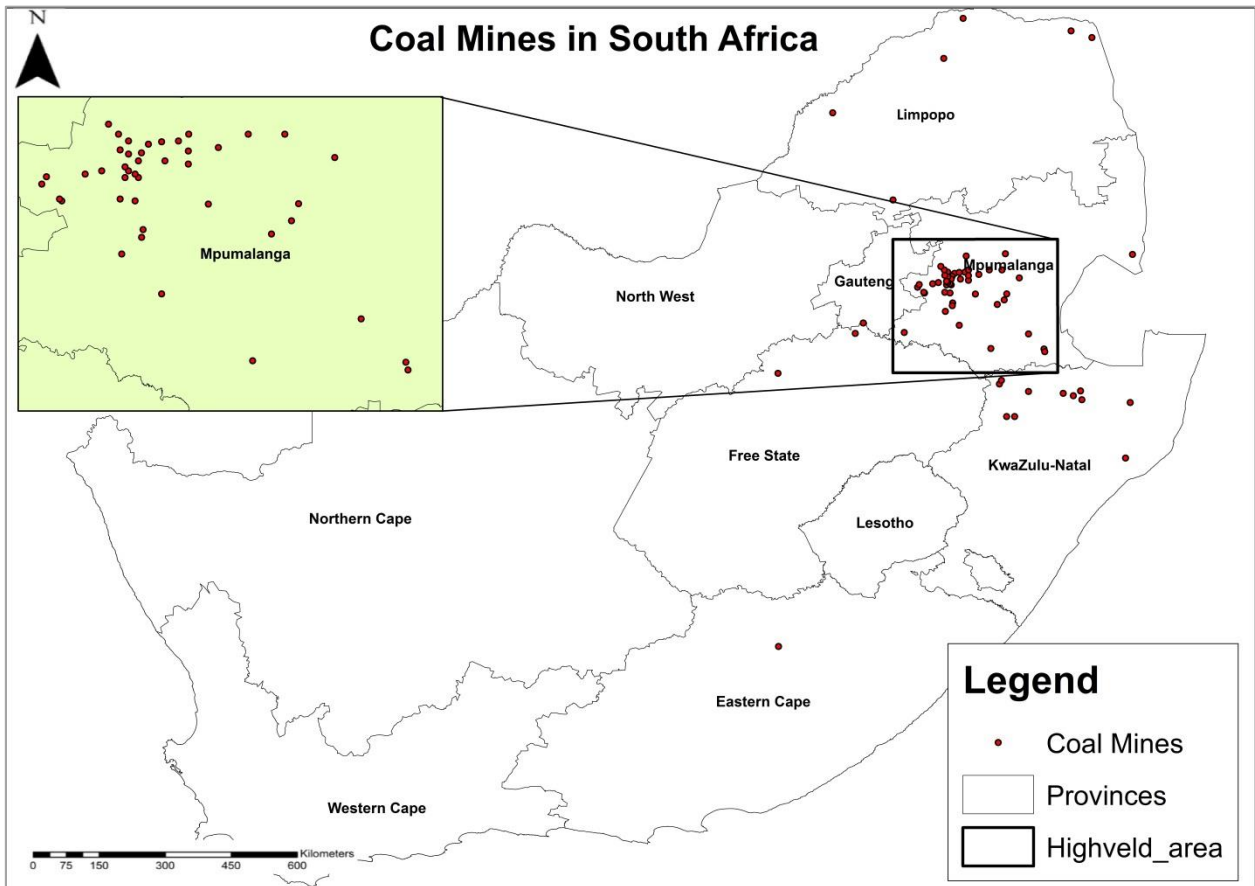


Figure 2-5. Coal mines in South Africa, providing coal for surrounding low-income settlements to be used for residential solid fuel burning

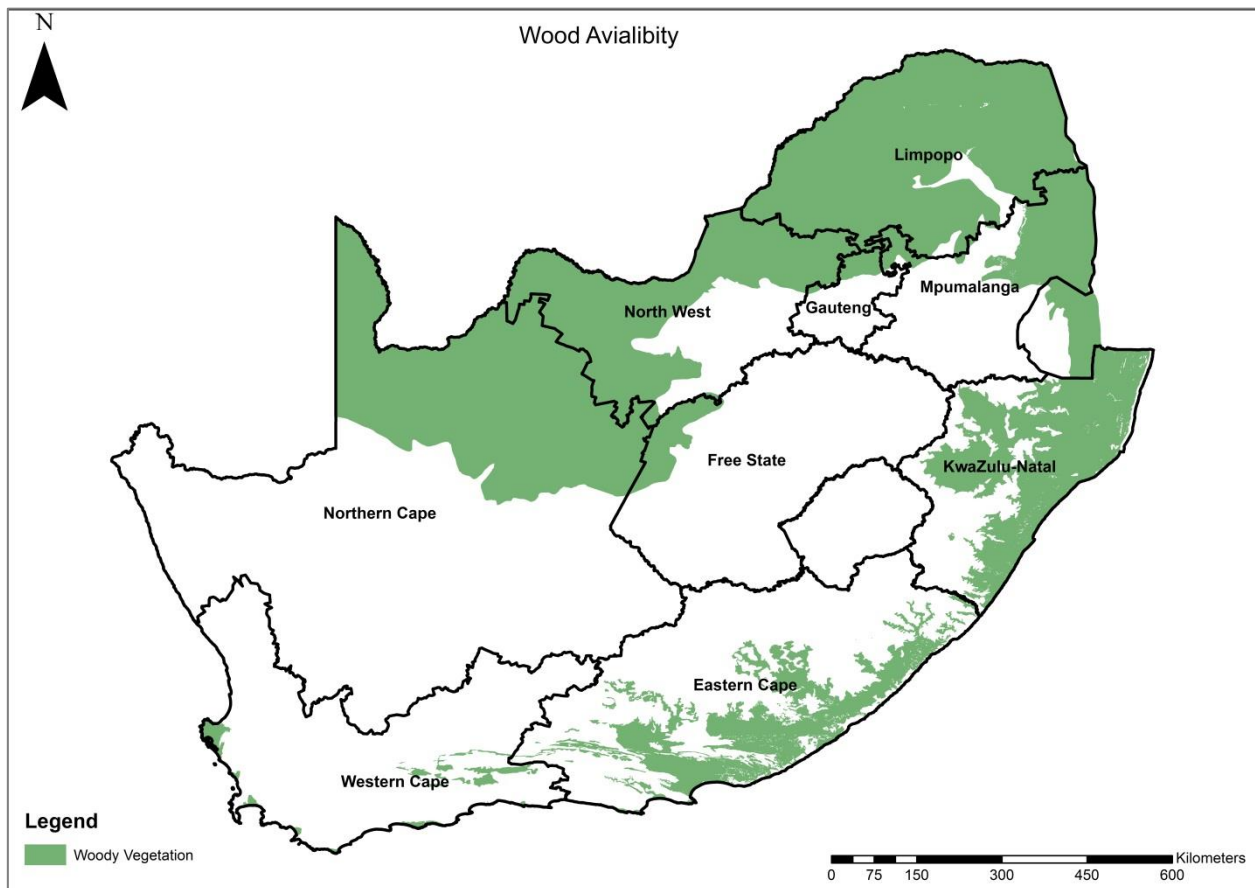


Figure 2-6. Biomes with woody vegetation, enabling the use of wood in surrounding low-income settlements for residential solid fuel burning

2.3 Regulatory instruments for managing air quality

In this section, the focus will be on the various regulatory instruments being used to manage air quality. The current air quality legislation of SA is described, followed by air quality monitoring in SA and then air dispersion modelling will be discussed in more detail with sub-sections focusing specifically on 1) AERMOD dispersion model, 2) current literature when modelling intra-urban ambient air quality using Gaussian dispersion models, 3) uncertainties on model inputs when using a Gaussian dispersion model, AERMOD, to simulate intra-urban ambient air quality, and 4) evaluating the modelling of air quality.

2.3.1 Legislation

In the following section, SA's current air quality legislation is outlined. Historically, SA's operative air quality control was delayed as legislation and cooperative governance was absent, but the declaration of the NEM: AQA No. 39 of 2004 was a significant moment in the progress of SA's air quality management. The Atmospheric Pollution Prevention Act (APPA) was generally perceived as the reason why concentrated air polluted areas were caused by industrial development. Critics

argued that the APPA did not control other impacts such as emissions, noise, odour, etc. efficiently (EVASS, 2017). The NEM: AQA No.39 of 2004 moved the emphasis of air quality management from control over a source to the impact on a receptor (Godwana Environmental Solutions, 2016). This conversion was in line with the Constitution of SA to provide an environment that is not harmful to the health of people living in SA.

To endorse this Constitutional right, the NEM: AQA delivered the framework to institute National Ambient Air Quality Standards (NAAQS) and an inclusive list of activities that require licensing, due to their potential for negative impact on the environment. The listed activities were initially established in 2010 and revised in 2013. The NAAQS may be achieved on a national level if the emissions from these activities are regulated on local to regional level.

Unfortunately, the effective implementation of air quality management is still an ongoing battle as SA is highly dependent on coal to support the energy-intensive industrial and mining divisions, continuous household fuel burning for cooking and space heating purposes. The continuous need for job creation and ongoing economic development also challenges the realisation of effective air quality improvements (Scorgie, 2012).

In this document, the NEM: AQA No. 39 of 2004 is described as follows (SA, 2004):

“To reform the law regulating air quality in order to protect the environment by providing reasonable measures for the prevention of pollution and ecological degradation and for securing ecologically sustainable development while promoting justifiable economic and social development; to provide for national norms and standards regulating air quality monitoring, management and control by all spheres of government; for specific air quality measures; and for matters incidental thereto.”

The NEM: AQA No. 39 of 2004 states that the current quality of ambient air in many areas of SA is not contributing to a healthy environment and this is causing an even larger problem concerning health impacts, affecting the disadvantaged the most. The polluters rarely weigh the great social, economic or environmental cost, and atmospheric emissions depleting the ozone and greenhouse gases harm the environment both locally and globally. This is in conflict with the constitutional right for everyone to have safe atmospheric conditions not endangering their health and for the environment to be conserved for the use of current and future generations to come. Appropriate legislative measures should be in place to ensure that pollution is inhibited, the natural habitat is not endangered, and conservation thereof is encouraged, guaranteeing sustainable environmental growth and using it moderately and safely (National Environmental Management Air Quality Act, 2004). If it is required to enforce more control and create cleaner manufacturing processes to safeguard cleaner and healthier air quality, the National Environmental Management Air Quality Act of 2004 states that it should then be endorsed by the Parliament of the Republic of South Africa. The NAAQS (SA, 2009) is outlined in Table 2-1 (Government Gazette, 24 Dec 2009 (No. 32816)).

Table 2-1: The amended National Ambient Air Quality Standards (SA, 2012)

National Ambient Air Quality Standards for Sulphur Dioxide (SO₂).			
Averaging period	Concentration	Frequency of Exceedance	Compliance date
10 minutes	500 µg/m ³ (191 ppb)	526	Immediate
1 hour	350 µg/m ³ (134 ppb)	88	Immediate
24 hours	125 µg/m ³ (48 ppb)	4	Immediate
1 year	50 µg/m ³ (19 ppb)	0	Immediate
The reference method for the analysis of SO ₂ shall be ISO 6767			
National Ambient Air Quality Standards for Nitrogen Dioxide (NO₂).			
Averaging period	Concentration	Frequency of exceedance	Compliance date
1 hour	200 µg/m ³ (106 ppb)	88	Immediate
1 year	40 µg/m ³ (21 ppb)	0	Immediate
The reference method for the analysis of nitrogen dioxide shall be ISO 7996			
National Ambient Air Quality Standards for Particulate Matter (PM₁₀).			
Averaging period	Concentration	Frequency of exceedance	Compliance date
24 hours	75 µg/m ³	4	01-Jan-15
1 year	40 µg/m ³	0	01-Jan-15
The reference method for the determination of the PM ₁₀ fraction of suspended particulate matter shall be EN 12341			
National Ambient Air Quality Standards for Particulate Matter (PM_{2.5}).			
Averaging period	Concentration	Frequency of exceedance	Compliance date
24 hours	65 µg/m ³	4	Immediate
24 hours	40 µg/m ³	4	01-Jan-16 – 31 Dec-29
24 hours	25 µg/m ³	4	01-Jan-30
1 year	25 µg/m ³	0	Immediate
1 year	20 µg/m ³	0	01-Jan-16 – 31 Dec-29
1 year	15 µg/m ³	0	01-Jan-30
The reference method for the determination of PM _{2.5} fraction of suspended particulate matter shall be EN 14907			
National Ambient Air Quality Standards for Ozone (O₃).			
Averaging period	Concentration	Frequency of exceedance	Compliance date
8 hours (running)	120 µg/m ³ (61 ppb)	11	Immediate
The reference method for the analysis of ozone shall be UV photometric method as described in SANS 13964			
National Ambient Air Quality Standards for Benzene (C₆H₆).			
Averaging period	Concentration	Frequency of exceedance	Compliance date
1 year	5 µg/m ³ (1.6 ppb)	0	01-Jan-15
The reference method for the sampling and analysis of C ₆ H ₆ shall either be EPA compendium method TO-14 A or method TO-17			

National Ambient Air Quality Standards for Lead (Pb).			
Averaging period	Concentration	Frequency of exceedance	Compliance date
1 year	0.5 µg/m ³	0	Immediate
The reference method for the analysis of Pb shall be ISO 9855			
National Ambient Air Quality Standards for Carbon Monoxide (CO).			
Averaging period	Concentration	Frequency of exceedance	Compliance date
1 hour	30 mg/m ³ (26 ppm)	88	Immediate
8 hour (calculated on 1 hour averages)	10 µm/m ³ (8.7 ppm)	11	Immediate
The reference method for the analysis of CO shall be ISO 4224			

The implementation of the NEM: AQA in 2004 moved the management focus of air quality from emissions control to primarily evaluating the problem based on ambient concentrations of pollutants. The ambient concentrations are derived from a multitude of sources, which include industry, natural, fugitive and domestic sources. To date, management of ambient concentrations has focused on controlling emissions from industrial sources; these are scheduled activities and the processes to enforce emission standards are simple, but when non-scheduled emissions are considered, such as domestic fuel burning, the legislative methods become more complex.

2.3.2 Air quality monitoring

Ambient air quality monitoring is the methodical, long-term assessment of pollutant levels by measuring the amount and types of pollutants in defined geographical areas in the outdoor air. Ambient air quality is the primary assessment criteria for defining air quality as a problem or not as well as the starting point of any management strategy process. Different methods of air quality monitoring are available, depending on the pollutant's complexity, reliability and detail of data required, and range from passive sampling systems to very sophisticated remote sensing campaigns (US EPA, 2015). The appropriate monitoring system and its location should be chosen in accordance with the end purpose in mind, considering investment costs, operating costs and the reliability of the chosen system. Different kinds of monitoring systems include permanent fixed-site (trend) monitoring, ambient source-linked monitoring, exposure monitoring and biological monitoring (Morgan, 1977). In Figure 2-7 and Figure 2-8 it can be seen that PM ambient monitoring stations are mostly positioned in population centres as human health plays a vital role in South African air quality management. In most air quality monitoring campaigns, government's guidelines will be given on where monitoring should take place, for instance, a location of particular concern such as schools or hospitals. Lastly, data retrieved from the monitoring system must be stored in a data management database, to later be studied in order to determine what is made known in terms of accuracy of modelling, health impacts and how effective regulatory standards are being implemented. In order

to implement a meaningful regulator platform, the correct process to monitor the air pollutants is vital to ensure quality data (US EPA, 2015).

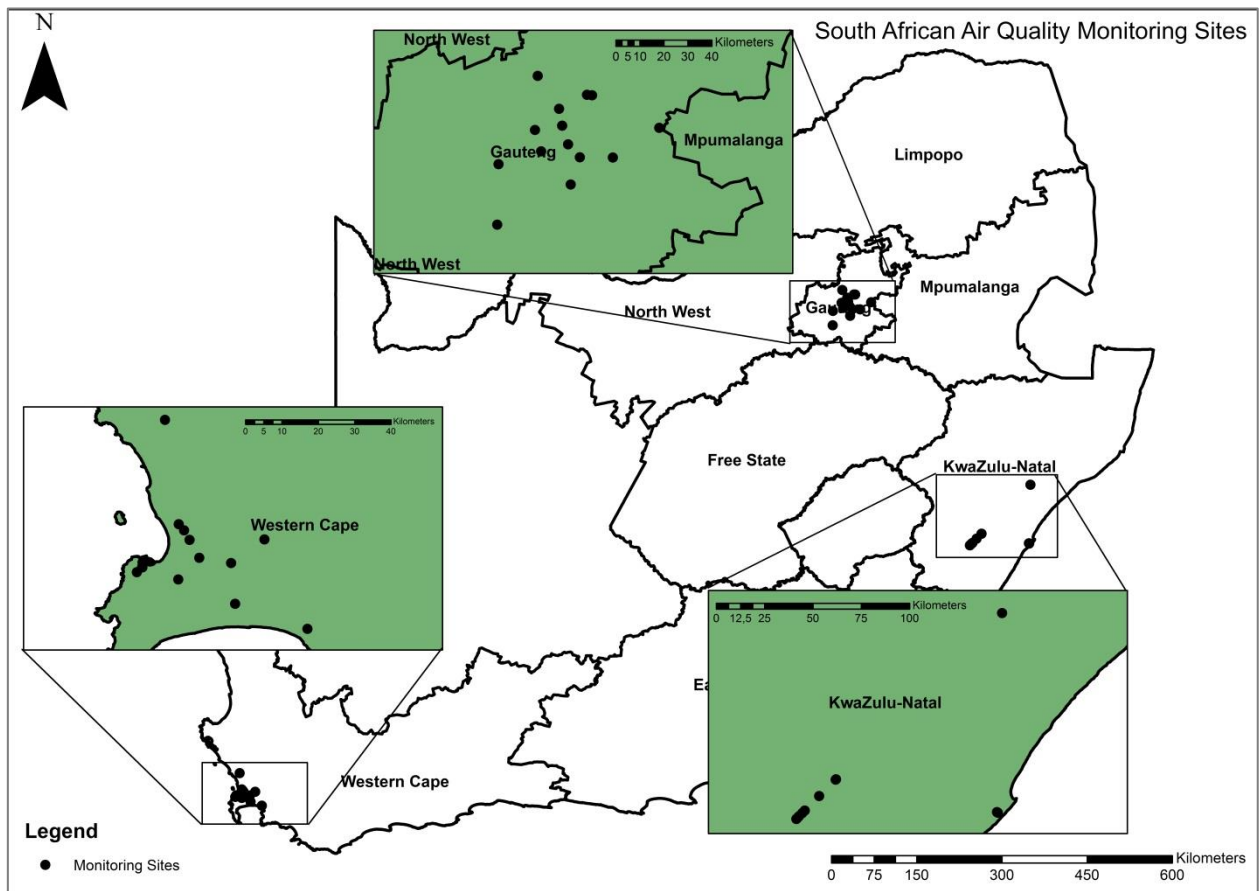


Figure 2-7. Monitoring sites measuring PM₁₀ in South Africa (SAAQIS, 2014)



Figure 2-8. Monitoring sites measuring PM₁₀ in Mpumalanga, the high priority area (SA, 2011)

Another reason for ambient air quality monitoring is the support and creation of air quality management plans; these plans are tasked with the determination of the existing state of air quality in a region, how it has been varying over the past years, and what can be done to guarantee good air quality in the future of that specific region. Goals and objectives are set for a region, outlining the short- and long-term policies and controls on how to improve air quality. Participation of the government, industry, businesses, non-governmental organisations (NGOs) and the people of that region will, however, determine the achievement of the region’s goals and objectives for improving ambient air quality. Three air quality priority areas have been identified in South Africa: the Highveld, Vaal Triangle and Waterberg-Bojanala. Each of these areas’ priority declarations and regulations can be found on the SAAQIS database, as well as other regions’ air quality management plans. The public can also report poor air quality incidents on the SAAQIS website. Monthly ambient air quality reports of the national priority areas are available for the public to see, thereby informing the country of what is being done to improve ambient air quality in South Africa.

2.3.3 Air dispersion modelling

According to South Africa’s Environmental Management Framework Guideline (SA, 2012), air dispersion modelling is a key tool in air quality management. With the atmosphere being dynamic and having various chemical and physical processes taking place all the time, air pollutants are

dispersed and transported from their source area, after which it is mixed and diluted, chemically transformed and lastly removed through deposition (SA, 2006). Data about polluting sources and meteorological circumstances is used by an air dispersion model to determine how a pollutant will disperse and what the pollution concentration of a certain pollutant will be at particular points (Zanetti, 1993). According to the DEA (SA, 2006), models describing the dispersion and transport of air pollutants in the atmosphere can be distinguished on the following grounds: on the spatial scale (global, regional-to-continental, local-to-regional, local), on the temporal scale (episodic models, statistical long-term models), on the treatment of the transport equations (Eulerian, Lagrangian models), on the treatment of various processes (chemistry: wet and dry deposition) and on the complexity of the approach.

Another method categorises dispersion models as follows: Gaussian models, semi-empirical models, Eulerian models, Lagrangian models, receptor models and stochastic models (Zannetti, 1993). Gaussian models are based on the assumption that plume concentration, at each downwind distance, has independent Gaussian (normal) distributions both in the horizontal and in the vertical dimensions. Many models are modified to incorporate special dispersion cases. These models are regarded as the most common type of air pollution models and can be used to calculate long-term averages.

It is necessary for a model to be able to both simulate the current state of the physical-chemical system and calculate how the system will respond with expected or formerly unmeasured pollution concentrations. It is therefore vital for a model to be built accurately enabling it to simulate real physical-chemical processes in the atmosphere (Dennis *et al.*, 1996). Dispersion models can be used in risk analysis, emergency planning, source apportionment studies, supporting the emissions-control policy and various regulatory and conservation assessments, as these problems are complex. Another advantage of dispersion models is the economic aspect of cost-effectiveness that needs to be taken into account. The choice of when which dispersion model should be used is based on the specific needs of the scenario being modelled.

The range of available models increases progressively in stages of user expertise, mathematical sophistication, and input data requirements. Category I, or referred to as intermediate models, includes the US EPA SCREEN3 model (a screening version of the Industrial Source Complex model (ISC3)) and is used for worst-case meteorology only (Berkowicz *et al.*, 1987). Category II is advanced models that require a desktop PC; they use local steady-state meteorology. These models also use one of the most recent theories of atmospheric stability such as Monin-Obukhov's similarity theory. Some examples of these advanced models are the EPA models: ISC3, AERMOD and the British Atmospheric Dispersion Modelling System (ADMS) (Carruthers *et al.*, 1994). Category III models can handle changes in meteorological conditions and atmospheric chemistry such as CALPUFF. Contrary to ambient monitoring, dispersion modelling is not limited to the measurement

of concentrations at specific monitoring locations; where some pollutants exist in trace amounts being costly and difficult to measure, dispersion modelling assists in saving time, effort and money. Dispersion models are useful tools in air quality assessments, but it is important to acknowledge the associated limitations and capabilities. An estimation of ambient air quality concentrations and deposition results because of scientific calculations (therefore high-quality input data), and is vital as it determines the model output. Although the assembly of all the essential input data can be challenging, it should be done thoroughly. Emissions data, meteorology, the type of model and model parameterisation are crucial areas of modelling input influencing the output (Esmen & Marsh, 1996). When a direct evaluation needs to be made between modelled and measured data for a specific time and locality, some trouble can arise as most models give output data in the form of operator defined spatial and temporal averages (DEA, 2006).

Modelling guidelines are a very important part of a country's air quality regulating system as this standardises model applications for regulatory purposes, making sure that dispersion modelling takes place in an acceptable manner, is of good quality and can be used to compare with other modelled or monitored results. The modelling guidelines should also ensure reliability and accuracy in the applications of models. Providing necessary techniques and practices must ensure standardisation and uniformity when considering pollution releases to the atmosphere when using dispersion models so that, for instance, all emission license applicants are treated rightfully. The modelling guidelines are intended to assist modellers step-by-step in the following (SA, 2014): a) outlining the assessment objectives and scope of the modelling study, b) selecting the most suitable model for the task based on the required air quality assessment levels and conditions, c) selecting the correct input data for the model to accomplish required calculations (emissions, meteorology, terrain data), and d) offering valid modelling results for the regulatory authority to make an educated judgement. Dispersion modelling has gained recognition as a regulatory tool when pollution source impacts under various meteorological conditions are assessed and air quality models are one of the only tools that can predict and evaluate potential impacts of possible pollution scenarios.

In 2005, an EPA Regulatory Model (AERMOD) was adopted as the EPA's level 2 preferred regulatory model for simple and complex terrain and it is used all over the world (US EPA, 2004). AERMOD is also one of the preferred dispersion models as stated by the DEA (SA, 2014), considering its features and capabilities, and has been used to model intra-urban air quality before (Cimorelli *et al.*, 2004; Kumar *et al.*, 2006; Paine *et al.*, 2006; Kesarkar *et al.*, 2007). An overview of AERMOD's features and capabilities and different parameter options are outlined in Figure 2-9 and Table 2-2. It models short-range pollution needed when modelling intra-urban air quality, although it is still not able to model the air quality at the exact location of the source. It also takes urban/rural terrain into account as well as different source types as intra-urban air quality will have pollution caused by various sources.

2.3.3.1 AERMOD, a Gaussian dispersion model

AERMOD is an atmospheric dispersion modelling system that includes the American Meteorological Society/Environmental Protection Agency Regulatory Model Meteorological Processor (AERMET), and the American Meteorological Society/Environmental Protection Agency Regulatory Model terrain pre-processor (AERMAP). One of the US EPA Regulatory Models is a Gaussian-type plume dispersion model based on planetary boundary layer theory, and also includes plume rise model enhancements (PRIME) and building downwash algorithms (Seangkiatiyuth *et al.*, 2011). These models depend on Gaussian plume equations and use assumptions about deterministic procedures to approximate pollutant concentrations at specific locations or areas. This is done by using data of emissions, topography and meteorological conditions (Bellander *et al.*, 2001; Cairncross & Mtiya, 2013).

Geographical information systems (GIS) are used in conjunction with dispersion models, enabling analysis of data both from the population distribution and the observed monitoring systems, which is an important issue concerning health impacts (Croner *et al.*, 1996). Adding the data representing the topography and land-use of the study area, the road network and traffic observations can make dispersion models even more accurate. AERMOD is designed to best calculate the dispersion of local pollution sources for a short range of 50 kilometres or less. AERMOD characterises field measurements by flat or complex terrain, urban or rural conditions and elevated or surface releases with or without building wake effects (Perry *et al.*, 2005). Nearly neutral or convective atmospheric conditions occur in urban areas and they are automatically handled by means of inputs of surface roughness length and building geometries (Cimorelli *et al.*, 2005). As different source classes were analysed, it was found that concentrations from all sources are sensitive to surface roughness (Faulkner *et al.*, 2008). The height at which the mean horizontal wind speed is zero is the surface roughness. The effect of building wakes is taken into account as it increases vertical turbulence to account for the 'convective-like' boundary layer found in night time urban areas (Cimorelli *et al.*, 2005). Unfortunately, currently, the AERMOD model only calculates dispersion at some distance away from the source (up to 50km), which is not satisfactory (Kesarkar *et al.*, 2007), and this is referred to as 'near source' dispersion. With intra-urban ambient air pollution, on the other hand, the model is required to calculate the pollutant concentrations at the exact same location as the source, with, for example, domestic fuel burning, referred to as 'intra-urban' dispersion.

A Categorical Exclusion - Certificate of Eligible (CE-CERT) tracer study suggested that dispersion models used for regulatory applications usually underestimate the lower range of the pollutant concentrations and overestimate high pollutant concentrations in the near field (Venkatram *et al.*, 2004).

The AERMET meteorological data pre-processor requires the following surface characteristic variables as input: temperature, wind direction, wind speed and cloud cover. With this AERMET

calculates friction velocity, Monin-Obukhov length, temperature scale, surface heat flux, convective velocity scale, vertical dispersion and mixing height (Cimorelli *et al.*, 2005). The way in which meteorological data is evaluated and how the parameters are attributed is vital – especially the Monin-Obukhov length scale, the boundary layer height and surface roughness (Hall *et al.*, 2000). This data can be collected from various or specific surface stations and upper air stations, specifically relevant to the modelling location. AERMET does boundary layer calculations in three stages, first reading the surface and upper air data files to determine if there are missing data values or values out of range, then it merges the two datasets, and lastly, it reads the merged data to calculate the boundary layer variables to create the surface profile needed in AERMOD (Stein *et al.*, 2007). AERMAP is the terrain pre-processor incorporating the relationship between air pollutants dispersing in the air and terrain features allowing the dispersion model to simulate the effects of air flowing over hills or splitting to flow around hills, and it also produces location and height data for each receptor location (US EPA, 2004).

Guidelines on how to use the AERMOD dispersion model are available from the US EPA website (US EPA, 2004), and SA also has its own modelling guidelines document (SA, 2014). In the following section of Chapter 2, available modelling guidelines and the lack thereof for specific intra-urban scenarios are discussed in more detail.

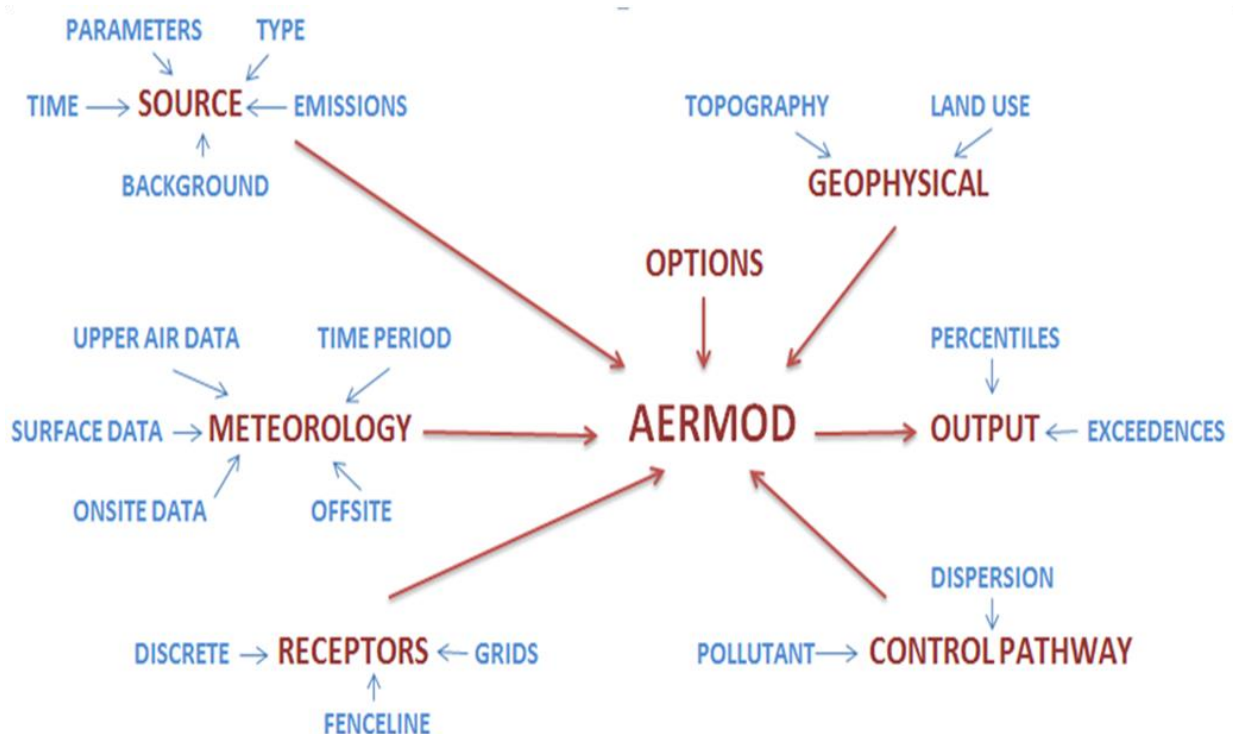


Figure 2-9. Diagram displaying different modelling parameter options

Table 2-2: An overview of the capabilities of AERMOD (US EPA, 2004)

Capability	Possible Modelling Options
Application	50 kilometers or less from source
Source type	line, point, volume, area
Source releases	surface, near surface, elevated
Source locations	urban/ rural
Concentration distribution	advanced Gaussian plume model
Plume rise	Briggs empirical expression
Boundary layer structure	L _{MO} scaling
Plume deposition	dry / wet from either gas/ particulates
Terrain type	simple/ complex
Building effects	PRIME downwash algorithms

2.3.3.2 Current literature on modelling intra-urban ambient air quality using Gaussian dispersion models

Effective urban air quality management to ensure healthy air for the current and future generations is of utmost importance. The impact of air pollution on climate, the environment and human health has been considered since the great smog event that took place in London, UK in 1952 (Brunekreef & Holgate, 2000). Air pollution concentrations causing health impacts are most likely to be at their worst in urban settlements where a combination of activities take place. Rodgers and Williamson (1982: 463) predicted that 3.2 billion people will be living in urban areas by 2000. Today, 54% of the world's population is urbanised, being a total of 3.8 billion people (WHO, 2014). More than half of the world's population lives in urban settlements and inhale the polluted air every day. In South Africa, 64% of the total population resides in urban settlements (The World Bank, 2015).

Every intra-urban scenario is unique and this makes modelling these ambient air quality conditions complex as variability is difficult to account for. At present, regulatory instruments' emphasis is on industries and other less intricate circumstances that can be comprehended and influenced fairly easily. Emissions caused by intra-urban sources, especially in low-income settlements, are remarkably difficult to understand, quantify and model, being even more challenging to apply effective control to in reality.

Even though dispersion models have limitations, they remain indispensable to use in air quality assessment studies. In some areas, adequate monitoring data is not available and dispersion models can be used to assess air quality instead. Information on a future projection of pollution levels or the prediction of future concentrations of a specific pollutant can be offered by these models in a relatively time- and cost-effective manner. These models also play an important role in the planning and decision-making process of pollution control policies (DEA, 2006).

Different techniques can be used such as proximity-based assessments, statistical interpolation, land use regression models, integrated emission-meteorological models (IEM), hybrid models and dispersion models. Proximity models use the most basic approach to comprehending intra-urban air pollution exposure by analysing the correlation between air pollution and health effects, assuming that nearby contact with emission sources surrogates for human population exposure. Although this method is simple, it does have considerable limitations (Venn *et al.*, 2001). Statistical interpolation is dependent on deterministic and stochastic geo-statistical techniques and this technique's leading advantage compared to proximity models is the use of real pollution measurements when calculating exposure estimates (Jerret *et al.*, 2005). Land-use regression models investigate pollution concentrations at a specific site based on surrounding traffic and land-use characteristics. The main advantage of this model is the ability to transform local areas through the empirical structure of regression maps without further monitoring or additional data, and it also assists in identifying locations in need of more intensive monitoring (Briggs, 2000; Sahsuvaroglua *et al.*, 2006). IEM models pair chemical and meteorological modules together to simulate the dynamics of air pollutants (Frohn *et al.*, 2002; Tilmes *et al.*, 2002). Unfortunately, this method is costly as high-end computational facilities, sophisticated software and highly competent and skilled personnel are needed to implement and run these IEM models. Hybrid models combine individual and regional monitoring with other pollution exposure methods and can be divided into two groupings: the first, combining personal or household exposure monitoring with one of the preceding methods and the second, combining two or more of the preceding methods with regional monitoring (Jerret *et al.*, 2005).

Dispersion models are considered to be more practical and reliable than other models and they can be used to model on a regional and intra-urban scale (Gryning *et al.*, 1987; Cyrus *et al.*, 2005). As previously mentioned, the dispersion model, AERMOD, is prescribed as the level 2 preferred tool to model intra-urban air quality within the South African context as it is one of the U.S. Environmental Protection Agency's (EPA) regulatory models. These dispersion models were created in the United States of America, a first world country, not being challenged so vigorously with the specific air pollution challenges as in South Africa, and therefore the models are not necessarily adjusted to model these conditions properly and therefore need adjustments with the dispersion coefficients.

Another example of a big concern regarding modelling air pollution in urban settlements is the limitation of dispersion models being designed to measure pollutant concentrations a distance away from a source, whereas intra-urban pollution has the same location for both the receptor and the source (Gordon, 1988; Jerrett *et al.*, 2005). A detailed and accurate emissions inventory is necessary to run the AERMOD model as it requires thorough information on the sources that cause the pollution (Kumar *et al.*, 2006). Modelling intra-urban air pollution currently has the highest level of uncertainty as it is not clearly defined, and there are not enough guidelines for what combination of input options are most appropriate to use to obtain optimal output modelling results (Wheeler *et al.*, 2008). Some studies on the sensitivity of input parameters of dispersion models concluded that AERMOD is sensitive to changes in emission rates, albedo, wind speed, cloud cover, surface roughness, vertical dispersion and temperature (Kesarkar *et al.*, 2006; Hanna *et al.*, 2007; Faulkner *et al.*, 2008).

2.3.3.3 Uncertainties on model inputs when using a Gaussian dispersion model, AERMOD, to simulate intra-urban ambient air quality

This section will elaborate on the uncertainties associated with 1) the current literature and 2) the variability in available data. When studying the current literature on modelling intra-urban ambient air quality, some uncertainties arise as the process of modelling these scenarios needs more specific guidelines and clarifications in some areas. Secondly, as the input has a great impact on the output of the model, it is crucial to ensure the use of accurate data relevant to each model run, and therefore if there is a variability in available data, this could cause irregularity when modelling these scenarios and inaccuracy in the modelling results and more importantly, greatly impacting regulations to control ambient air quality.

Table 2-3 displays the current recommended modelling input options for intra-urban air quality as provided by the South African DEA (SA, 2014). It is clear that modelling intra-urban air quality is complicated and the current guidelines are not clear enough on all the modelling input options concerning these scenarios, causing some uncertainties and leaving room for error.

Table 2-3: Current recommended input options for modelling intra-urban air quality with AERMOD in South Africa (SA, 2014)

Description	Proposed input
Source	
Type	Urban regions consisting of multiple point sources can be combined to act as an area source.
Emission rate	Emission factors can be used to calculate the emission rate in [g/(s/m ²)]
Background emissions	It can be regional/local background sources, at least one year of monitoring data is advised as significant seasonal differences occur
Variable emissions	Characterise according to hourly/daily /monthly /seasonal variability
Averaging time	Annual/short-term periods (less than 24 hours) in compliance with NAAQS
Receptors and spatial resolutions	
Receptor grid	Multi-tier Cartesian grid with predefined grid spacing is recommended and if necessary a separate refined grid or discrete receptors should be placed in areas of concern such as pollution hotspots or sensitive receptors in the modelling domain
Resolution	This is a problem as the pollution concentrations need to be measured within the same location as the source, for example in the case of domestic solid fuel burning polluting the direct environment of the residents and not just from 50 meters away
Fence line	Fence lines are advised 50km by 50km centered for industrial sources but no fence line is advised for domestic sources
Geographical inputs	
Modelling domain	50 by 50 km centered for a flat terrain area or for a complex terrain the domain might need to be elongated.
Coordinate system	Universal Transverse Mercator (UTM) and all coordinates should be defined on the World Geodetic System 84 (WGS-84)
Classification of site	An area is defined as urban if it has less than 35% vegetation coverage or the classification method specified by the US EPA guideline should be followed
Meteorology	
Surface data	Hourly sequential is advised and temperature, relative humidity, wind speed, wind direction, solar radiation, cloud height and cloud cover are needed
Upper air data	At least two daily soundings are required and temperature, relative humidity, wind speed and wind direction are needed.
Sources of MET data	South African Weather Service (SAWS)
Data period	A minimum of 1-year on-site specific data or at least three years of appropriate off-site data must be used. The data should be from a period no older than five years to the year of assessment.

For each source, the model requires certain inputs: emission rate, source type, release height and location. The emission rate can be classified as the input parameter that is most complicated, but also most important to calculate, as this has a large impact on the results. To calculate the emission rate (ER), the fuel type must be specified, the emission factor (EF) of that fuel is needed and must then be multiplied with the activity rate (AR: quantity of fuel used per number of households per year).

The most commonly used fuels for domestic fuel burning in SA were considered: wood, coal, paraffin and LPG gas. The emission factors for each fuel, the activity rate for every fuel, the number of households using that fuel annually, the emission rate, the source release height and source type were, therefore, the chosen inputs focused on as indicated below:

1. Emission factor of wood
2. Emission factor of coal
3. Emission factor of paraffin
4. Emission factor of LPG gas
5. Activity rate of wood
6. Activity rate of coal
7. Activity rate of paraffin
8. Activity rate of LPG gas
9. Emission rate of wood
10. Emission rate of coal
11. Emission rate of paraffin
12. Emission rate of LPG gas
13. Emission rate of domestic fuel burning
14. Hourly time scale
15. Monthly time Scale
16. Source type
17. Source release height
18. Number of households using wood
19. Number of household using coal
20. Number of households using paraffin
21. Number of households using LPG

A review of the literature values for each input variable was done and the results are summarised and given in Chapter 4 in Table 4-3. This highlights the variability causing uncertainties of the different model inputs and supports the argument that confusion and inaccuracy are a large possibility if inputs are not handled with precision and precaution.

2.3.3.4 Comparison of modelled versus observed concentrations

It is necessary to evaluate the modelling of air quality because it is used to support laws and/or regulations that protect air quality. If the modelling results show that the model performed poorly, those results cannot be used for regulation purposes, but unfortunately evaluating a model's performance is complex as every modelling scenario has different inputs such as meteorological conditions, terrain information, source inputs etc., resulting in different outputs and model calculations. There can be guidelines on how to evaluate modelling results, but there cannot be one simple set of rules made applicable to all scenarios (Kumar *et al.*, 2006). The EPA began conducting evaluation studies in order to develop statistics that review the performance of numerous models that serve as guidelines for assessing modelling of air quality.

The following contribute to the uncertainties associated with an application of an air quality model: 1) model input errors, 2) errors in concentration observations, 3) errors in internal model parameters, 4) errors and omissions in model physics, as well as 5) random variations (Hanna *et al.*, 2007).

The evaluation of a model can be done in various ways, including Q-Q plots, Taylor diagrams or the comparison between simulated and observed concentrations that will show whether the model was conservative or optimistic.

A Q-Q plot consists of two datasets plotted against each other as quantiles; in other words, the plot indicates the fraction of points that fall below a given value. A 45-degree line is also plotted as a reference and a Q-Q plot displays how a number of different distributions or two similar distributions of chosen datasets differ from each other. Some of the advantages of Q-Q plots are that the sample sizes do not need to be similar and multiple distribution characteristics can be compared. AERMOD offers options for output files designed specifically to enable model evaluation; for instance, one type of file lists concentrations by rank, including only one value per rank (Langer & Klem, 2011).

Taylor diagrams display how closely a modelled pattern or a set of patterns match observed results. Two patterns' correspondence is calculated by their centred-root-mean-square difference, their correlation and the amplitude of their differences, which is represented by their standard deviations (Taylor, 2001). When a comparison of multiple aspects of complex models or an evaluation of a specific capability of various models needs to be made, these diagrams are particularly useful.

A sensitivity analysis can be described as: "to ascertain how a given model depends on its input factors" (Saltelli *et al.*, 2012). Model evaluation has generally proceeded by addressing the following aspects (Weil *et al.*, 1992): operational performance assessment determines how accurately the model predicts the high ground level concentrations (GLC) essential in assessing compliance with air-quality regulations. Next, model physics evaluation states whether the model is based on sound physical principles and whether it produces accurate predictions for the right reasons. Lastly, the model error must be separated from natural variability and the performance of two or more models must be distinguished. It is clear that detailed studies must be done to evaluate a model's

performance, using the correct input parameters and being able to compare the output with monitored measurements.

2.4 Study design

2.4.1 Problem statement

Air pollution models play an important role in local environmental policymaking. However, using Gaussian dispersion models, more specifically the proposed US EPA model called AERMOD, to govern urban air quality has some challenges that need to be addressed: the typical ambient PM concentrations in low-income urban areas need to be characterised; there are some uncertainties on how to simulate intra-urban air quality using a Gaussian dispersion model; these models are more sensitive to some inputs than others when modelling intra-urban air pollutants and they need to be highlighted; the relative contribution of different pollution sources is unclear, which raises an important question as it determines the significance of each pollutant when guidelines are made for regulatory purposes.

2.4.2 Research methodology

The first objective is addressed by characterising the ambient PM concentrations in various low-income urban areas on the South African Highveld (Chapter 4).

Objective 2 is addressed by doing an evaluation of the sensitivity of simulated ambient PM to model inputs in Kwadela, Mpumalanga, by comparing different dispersion modelling scenarios (using the AERMOD dispersion model, a proposed US EPA dispersion model) (Chapter 4). This is done to determine which variables have the most significant impact on the modelling results (output). Lastly, objective 3 is addressed by modelling and assessing the relative contribution of domestic fuel burning, windblown dust, waste burning and surrounding coal-fired industrial sources to PM₁₀ in Kwadela and compared with the one-hour average ambient measurements made during a winter monitoring campaign in 2013 (Chapter 5).

2.4.3 Limitations and underlying scientific principles of the study

This study has some assumptions and underlying scientific principles that need to be considered.

- One of the challenges when studying the character of low-income urban areas was the limited availability of data and, unfortunately, there were some data missing. High spatial variability contributes to uncertainties and challenges when studying and modelling these areas as every characteristic will differ, e.g. the fuel use for domestic fuel burning, land use, weather conditions, income level, availability of fuel resources, etc.

- It should also be noted that industrial coal-fired power stations were the only industrial sources of PM taken into account in the study within a 50km radius, and secondary particulates are not modelled and background data is not incorporated.
- The meteorological data used for all model runs was received from the Ermelo air quality monitoring site, 36km away from the study area. This monitoring site was chosen due to its proximity to the study area, but it should be noted that this influences the representativity of the data since topography, land use, and roughness length are inherently variable.
- This study focuses on a regulatory approach to evaluate how a regulatory tool performs in our environment.
- With regards to the evaluation of the sensitivity of simulated ambient PM to model inputs in Kwadela, Mpumalanga (objective 2), four different modelling scenarios with different variables were chosen and the difference in output based on the input was analysed, not comparing each parameter separately. If only one parameter was changed for every model run, the effect of each variable would have been clearer.
- Figure 4-8 shows that both the area source scenarios showed lower concentrations within the modelling domain than the point source scenarios. Since the same pollution masses were emitted for Scenarios 1 and 3, and Scenarios 2 and 4, an assumption was made that the plume then extended further for the area sources. For this study one of the concerns are the health impacts of intra-urban ambient air quality, being the ambient air quality close to the source, such as low income settlements. If the plume extended further, the receptors would not have included the results as the pollution levels of the direct environment of the source was of concern. However, some isopleths maps would have been useful to see this affect.
- In section 3.4.4.2 the area representing windblown dust as a pollution source does not cover the whole of Kwadela (the study area), but as the area of the dust reservoir reduced by a factor of vegetation cover. It has been suggested that the entire area (the whole of Kwadela) could have been designated a source, limiting emissions by a factor accounting for vegetation coverage and this could have proven to be a better method to represent windblown dust as a pollution source.
- To assess the applicability of the model in simulating intra-urban air quality, it would have been more effective to have multiple monitoring points to compare with simulated concentrations at these points as this would show the model's potential to simulate spatial variations in ambient concentrations at the intra-urban scale. This study was, however, limited to one specific monitoring station's results for comparison.

3. DATA AND METHODOLOGY

Introduction

This chapter includes the data and methods used to address the three objectives respectively.

Firstly, the study area, a low-income settlement called Kwadela, situated in Mpumalanga is introduced and the same study area was used in both results chapters (4 and 5). An overview of how five different low-income settlements were characterised (first objective) is given, as well as (objective 2) an outline of the method and the data used to evaluate the sensitivity of simulated ambient particulate matter to model inputs in Kwadela, Mpumalanga, by comparing different dispersion modelling scenarios.

Then the fourth objective is outlined where domestic fuel burning, windblown dust, waste burning and surrounding coal-fired industrial sources are modelled to assess their relative contribution to PM₁₀ in Kwadela. Lastly, the winter Kwadela Ambient Air Quality Monitoring Campaign of 2013 is explained as this campaign's monitored results are used in comparison with the modelled results in Chapter 5 to analyse the model's performance.

3.1 Study area: Kwadela, Mpumalanga

Kwadela is located on the South African Highveld next to the N17 between Bethal and Ermelo in Mpumalanga, as shown in Figure 3-1. Kwadela is situated in Mpumalanga and is part of the Msukaligwa Municipality. The town of Davel is located just north of Kwadela. In this study, windblown dust, domestic fuel burning, waste burning, local traffic and railroad traffic are considered as the main human-generated contributors to ambient air quality degradation of this community, although there are other, more distant, anthropogenic sources in reality as well. It should be noted that transportation sources' emissions contribute less compared to the previously mentioned sources because of the small population, limited roads, and fewer cars in Kwadela. Industrial emissions should also be considered although the nearby industries are situated +/- 45km away from Kwadela. The 2011 Census (SSA, 2011) divides Kwadela into six areas, referred to as 'small area layers', and the number of households was calculated per area as shown in Table 3-1 and Figure 3-3. The last 2011 census estimate indicated 984 households, with a total population of 3 777 people living in Kwadela. An aerial photograph is shown in Figure 3-2. The land-use around Kwadela is dominated by natural grasslands (63.21%) and cultivated commercial dry land (25.72% of the 19 600 km² surrounding area (Figure 3-4)). This distribution illustrates the limited woody fuel available for this low-income settlement. Although this settlement is surrounded by undulating terrain (Figure 3-5), Kwadela is located on somewhat flat terrain.

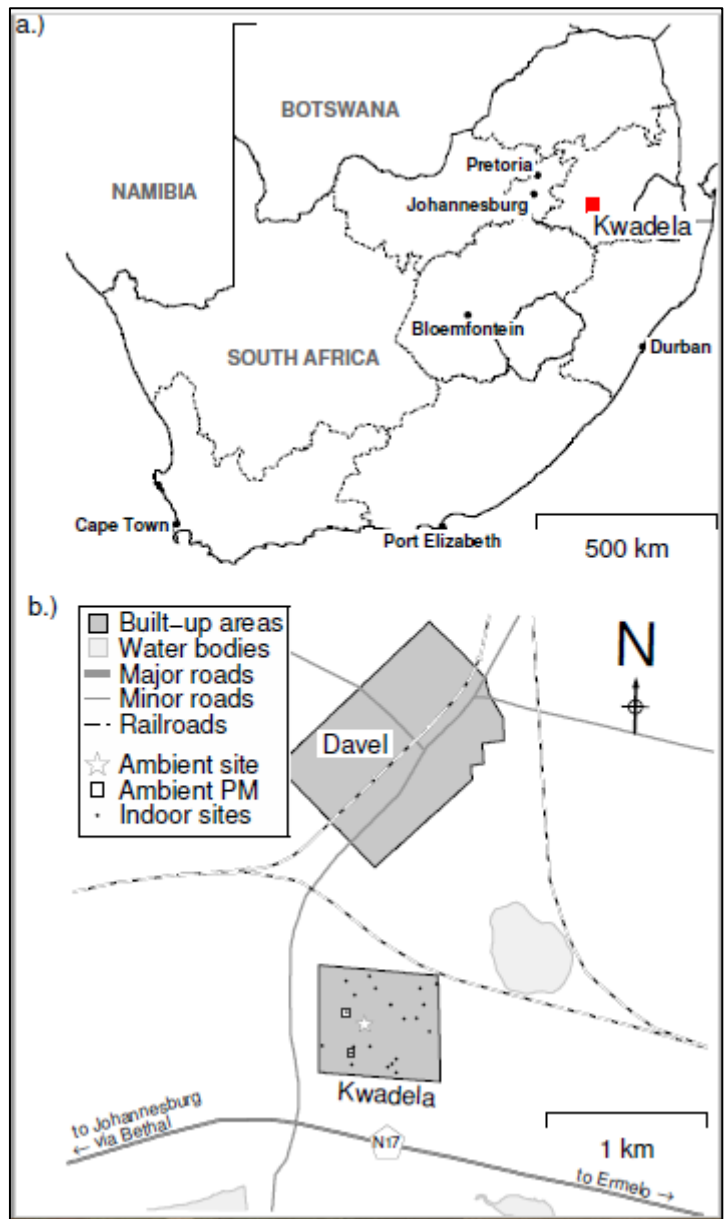


Figure 3-1. a) The location of Kwadela, Mpumalanga. (b) An expanded view of the area around Kwadela including the approximate location of the sampling sites

Table 3-1: Selected attributes for Kwadela of the 2011 census small area layers

Small area layer (SAL)	Households	Population	Area (km²)
8610070	114	462	11700
8610121	120	546	5790
8610129	123	567	12930
8610173	189	651	7500
8610178	201	654	5120
8610140	237	897	7340
	984	3777	



Figure 3-2. Satellite photo of Kwadela, Mpumalanga



Figure 3-3. A number of houses per area in Kwadela, Mpumalanga. Each colour indicates a different small area layer and the numbers indicate the households in that area. These figures were used to determine the number of domestic fuel burning sources in Kwadela

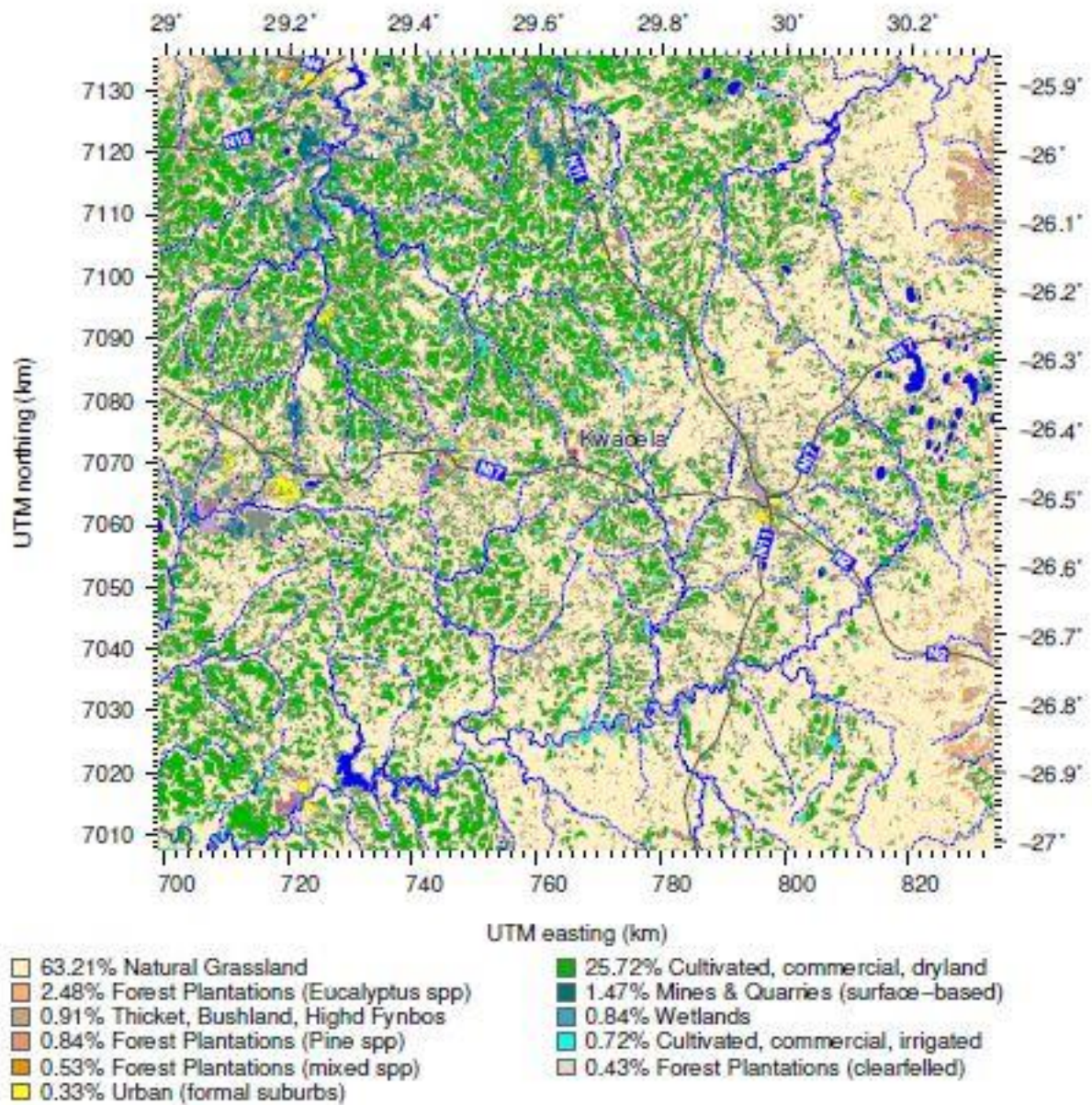


Figure 3-4. Land-use of the region around Kwadela, Mpumalanga

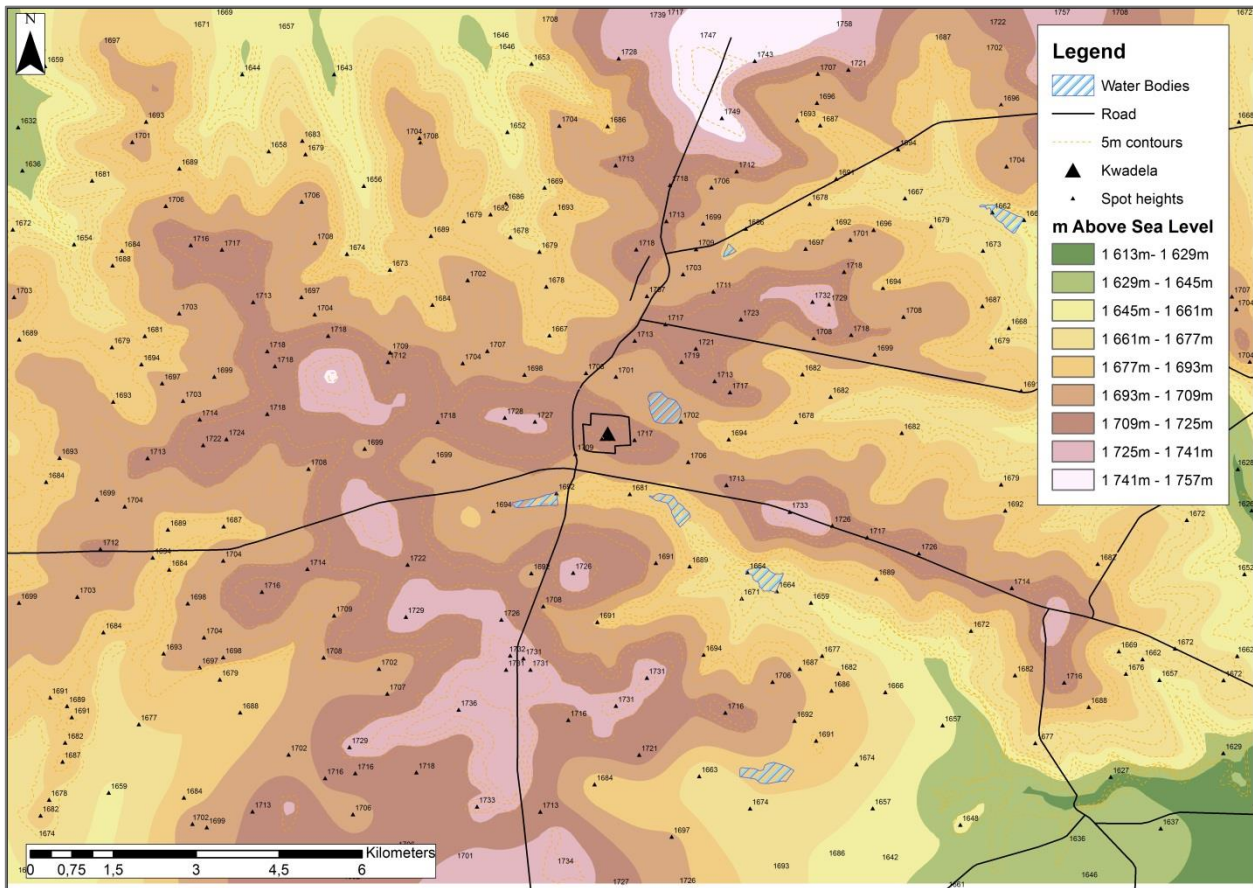


Figure 3-5. The topography of the region around Kwadela, Mpumalanga

AAQS for PM is exceeded, confirming that Kwadela has polluted air. The 99th percentile of the daily averaged PM₁₀ is 96µg/m³ and for PM_{2.5} it is 60µg/m³ (section 3.5). Judging from the diurnal profile of PM with peaks in the mornings and evenings, domestic fuel burning is mainly responsible for these high ambient PM values. This is noteworthy since Kwadela has less than 1 000 households and located +/- 45km from the nearest industrial source. This also implies that fuel for cooking purposes is enough to raise ambient PM levels to above air quality standards.

Kwadela was visited by the researcher to familiarise herself with the community and observe their behaviour and domestic fuel burning habits. During the day, the polluted air is being inhaled by a large group of the population, especially the women and the more vulnerable portion of the population: children and the elderly, staying at home. It is an affable settlement and the children play in the streets after school until sunset, some women and elderly walk around visiting each other and gather household supplies needed for dinner or the week ahead, thereby being outside and directly affected by the poor air quality.

In Kwadela, there is a coal sales area located in the middle of the settlement where residents can buy coal for heating and cooking purposes; it is affordable and easily accessible (Figure 3-6). Most households use different kinds of coal stoves and use various types of fuel, as shown in Figure 3-7,

Figure 3-8 and Figure 3-9. These coal stoves have chimneys (Figure 3-10) emitting low-level emissions contributing PM into the ambient air of Kwadela.



Figure 3-6. A heap of coal situated in Kwadela, used for domestic fuel burning among the residents



Figure 3-7. Wood is also used as a fuel in coal stoves in Kwadela, Mpumalanga



Figure 3-8. Type 1 coal stove used indoor in Kwadela, Mpumalanga



Figure 3-9. Type 2 coal stove used indoor in Kwadela, Mpumalanga



Figure 3-10. A chimney from a coal stove polluting and contributing to PM in Kwadela, Mpumalang.

This community is a small low-income settlement with pollution sources contributing on a smaller scale than, for example, a larger urban settlement. This creates the opportunity to evaluate the impact that the pollution of domestic fuel burning, as one of the dominant pollution sources, has on the ambient air quality.

3.2 Characterising the ambient particulate matter loading and variability of five low-income urban areas on the South African Highveld

The typical ambient PM concentrations in low-income urban areas, in Kwadela and four other low-income settlements, were analysed to characterise the typical ambient PM concentrations. Ambient PM₁₀ data was received from SAAQIS, and data was available for all these sites from 2004 to 2010.

Table 3-2: Locations of the low-income settlements analysed

Province	Number	Settlement	Latitude	Longitude
Johannesburg	1	Alexandra	26.1033° S	28.0976° E
	2	Sharpeville	26.6864° S	27.8751° E
	3	Sebokeng	26.5634° S	27.8339° E
Free State	4	Zamdela	26.8662° S	27.8692° E

3.2.1 Data quality control applied for each of the data sets of the low-income settlements

The general philosophy in quality assuring data is to firmly ignore data that is suspected to be from a faulty instrument. Extra care is taken when dealing with extreme values and outliers. These are not set to missing unless they are part of a time period where the instrument did not appear to be operating optimally.

The raw datasets collected are merged and processed into a final dataset for analysis through the following steps:

- Apply date and time corrections to each of the raw data files using the instrument logs
- Merge each of the datasets above into one uniform dataset.
- Apply masks to each instrument according to the instrument log.
- Perform automated quality control on each variable and flag problematic values.
- Test for sensible observation date and time values.
- Flag data below the instrument detection limit.
- Flag data above the instrument's maximum detectable limited.
- Test the gradient of each instrument against realistic response times.

- Test for spikes by comparing with values before and after.
- Test for stuck values and set missing.
- Flag climatological outliers.
- Flag outliers using the median absolute deviation.
- Each variable with its associated flags identified in the automated quality control is then reviewed manually by viewing time series plots. Each flag is carefully inspected and values are deemed real or set to missing if a problem is suspected.

3.3 Evaluation of the sensitivity of simulated ambient particulate matter to model inputs, by comparing different dispersion modelling scenarios

An evaluation of the sensitivity of simulated ambient PM₁₀ to model inputs in Kwadela, Mpumalanga, was done by comparing different dispersion modelling scenarios. Four model runs were done, each with a different scale of inputs. Two best case scenarios and two worst case scenarios. 'Best case' meaning pollution source inputs modelled with a probability of lower emission concentration results (e.g. lower ER and less point sources representing less houses burning domestic fuel) as opposed to 'worst case' meaning pollution source inputs modelled with a probability of higher emission concentration results (e.g. higher ER and more point sources representing more houses burning domestic fuel).

AERMOD dispersion model was chosen because it is the US EPA regulatory dispersion model advised to use for pollution simulations. As AERMOD is an advanced Gaussian plume and short-range (50km and less) model, it is ideal to use in this case study as intra-urban air quality needs to be measured from the same location as the source and outward. Domestic fuel burning is the source of pollution, using the four dirty fuels described in Table 4-3: wood, coal, paraffin and LPG gas.

3.3.1 Model setup

The AERMET processor was run with the following data and the output, as shown in Figure 3-11 and Table 3-3, was used to set up AERMOD for the evaluation of the sensitivity of simulated ambient PM to model inputs. Thereafter, the receptors were chosen, and all the calculations concerning the source inputs were done after objectives 1 and 2 were met, as the findings summarised in Table 4-3 in Chapter 3 were used to calculate emission rates.

3.3.2 Meteorology data of Kwadela, Mpumalanga

Hourly data collected from available onsite data (see below), from ERA-Interim and where missing data occurred from Ermelo (nr. "0479870 X" -26.50, 29.98) and Bethal (nr. "0478808 7" -26.462, 29.46) for the period 1 January until 31 December 2012 was used, focusing on the following

parameters: temperature, pressure, wind direction, wind speed, rainfall, and relative humidity. Three-hourly observations gathered by the Ermelo weather office were used to determine cloud base, cloud type and total cloud cover. The most recent available climate statistics (such as the WB40 tables) for Ermelo and Bethal were also used.

ERA-Interim is a global atmospheric analysis from 1979, constantly updated in real time. The data assimilation system used to produce ERA-Interim is based on a 2006 release of the integrated forecast system (IFS) (Cy31r2). The system includes a four-dimensional variational analysis (4D-Var) with a 12-hour analysis window. The spatial resolution of the dataset is approximately 80 km (T255 spectral) on 60 vertical levels from the surface. A wind rose of meteorology conditions around Kwadela in 2012 is displayed in Figure 3-11 as AERMET output.

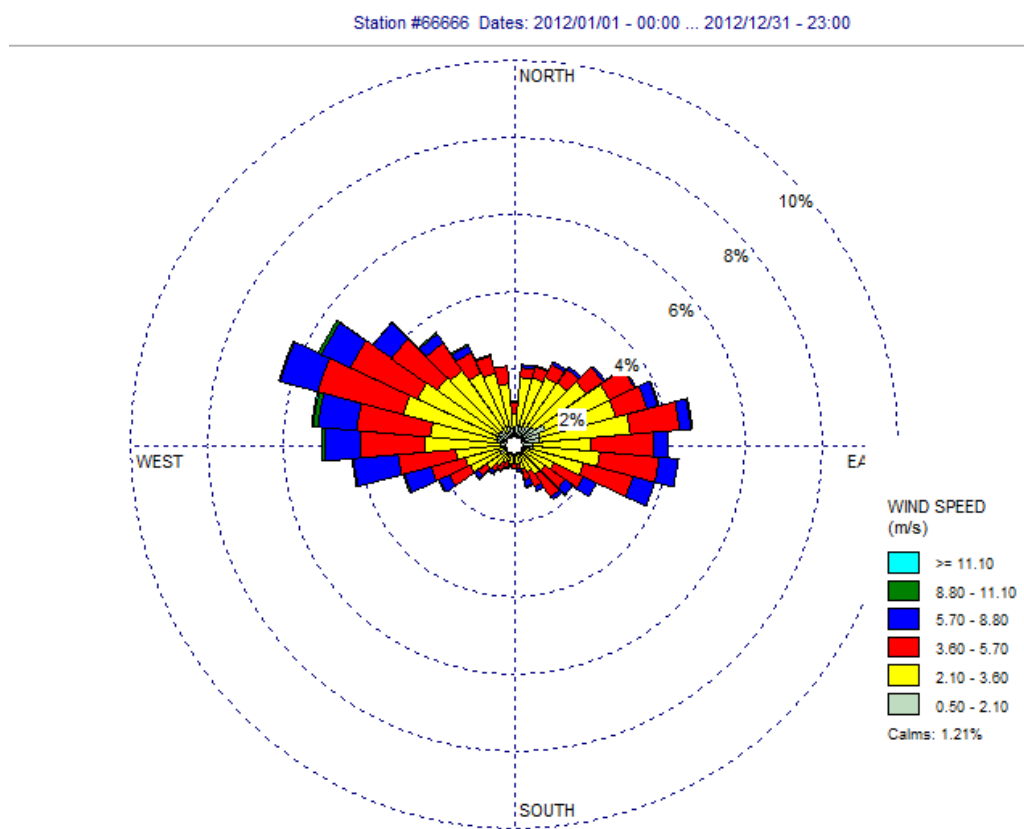


Figure 3-11. AERMET Wind rose of meteorology conditions around Kwadela in 2012

Table 3-3: AERMET data file information

	Year	2012
Total no. of hours		8784
Average wind speed		3.31 m/s
Calm records		106
Calm winds frequency		1.2%

3.3.3 Receptors used for all four model runs

The site-domain and terrain contours remained the same because all model runs were done on Kwadela. The terrain is fairly flat as shown in Figure 3-5. Figure 3-12 displays a street map of Kwadela and the three discrete receptors used in all four model runs placed at the three monitoring sites used in the Kwadela Ambient Air Quality Monitoring Campaign, and Figure 3-13 presents the uniform cartesian grid size used in all four model runs.



Figure 3-12. Open street map of Kwadela and the three discrete receptors used in all model runs placed at the three monitoring sites

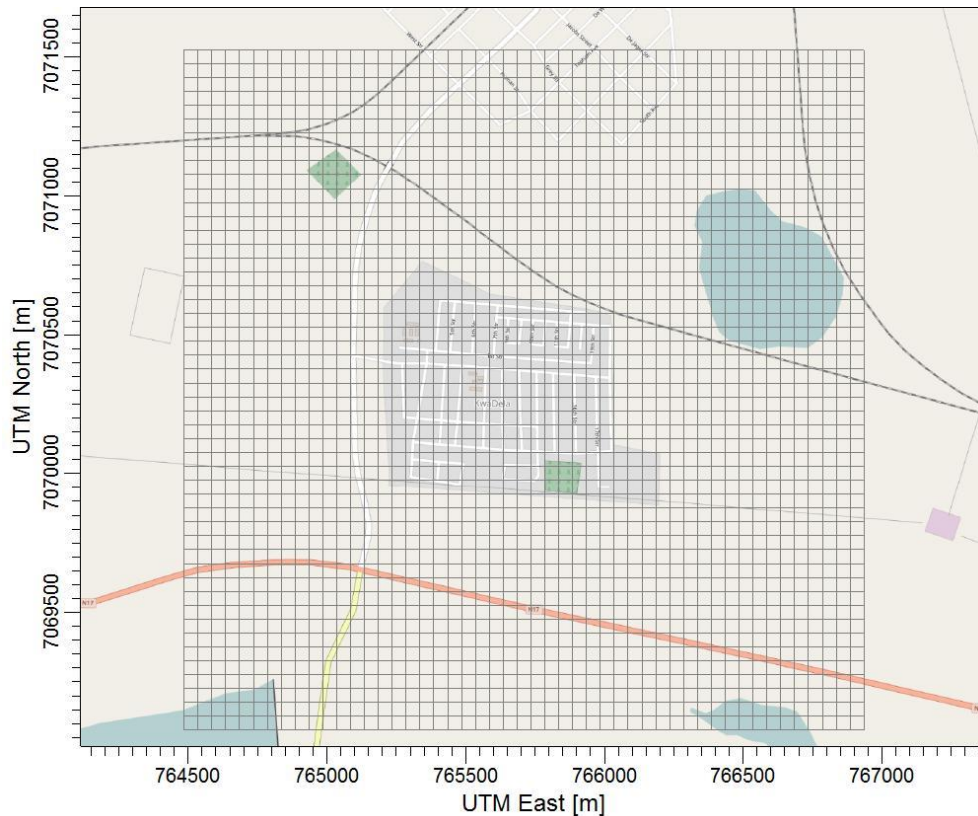


Figure 3-13. Uniform Cartesian grid used in all four model runs

3.3.4 Source characterisation

The source characterisation and emission calculations were some of the biggest challenges during this study. Firstly, the character of low-income settlements had to be outlined, then the uncertainties and variability in data when modelling these scenarios had to be defined. Those findings, all described in Chapter 4, were then used to guide the source characterisation and emission calculation processes of the evaluation.

To calculate the sources' emission rate (ER), the following equation was used:

$$\text{Emission rate (ER)} = \text{Emission factor (EF)} \times \text{Activity rate (AR)}$$

For model runs 1 and 2, referred to as 'best case scenarios', the lowest figures considered in the literature summarised in Table 4-3 were used to calculate the emission rates (ER): 0.01g/s/m² (rectangular area source) and 0.000022g/s (point source), respectively. For model runs 3 and 4, referred to as 'worst case scenarios', the highest figures found in the literature (Table 4-3) were used to calculate the emission rates (ER): 1.15g/s/m² (rectangular area source) and 0.0014g/s (point source), respectively.

As the model can present a source as a line, volume, area or point source, model runs 1 and 3 (one best case scenario and one worst case scenario) proposed domestic fuel burning as an area source

as shown in Figure 3-14 and model runs 2 and 4 (one best case scenario and one worst case scenario) proposed certain houses, each as a point source of domestic fuel burning (Figure 3-15 and Figure 3-16).

Table 3-4: Detailed source inputs for each model run

Model run	1	2	3	4
Pollutant	PM ₁₀	PM ₁₀	PM ₁₀	PM ₁₀
Source type	rectangular area	point	rectangular area	point
X-coordinate	765335.21	n/a	765335.21	n/a
Y-coordinate	7069964.16	n/a	7069964.16	n/a
Base elevation (m)	1699	n/a	1699	n/a
Release height (m)	1.2	3	1.2	1.2
Gas exit temperature (°C)	n/a	200	n/a	200
Gas exit velocity (m/s)	n/a	1.5	n/a	1.5
Stack diameter (m)	n/a	0.15	n/a	0.15
Pollutant averaging	1 hour, 24 hours, period	1 hour, 24 hours, period	1 hour, 24 hours, period	1 hour, 24 hours, period

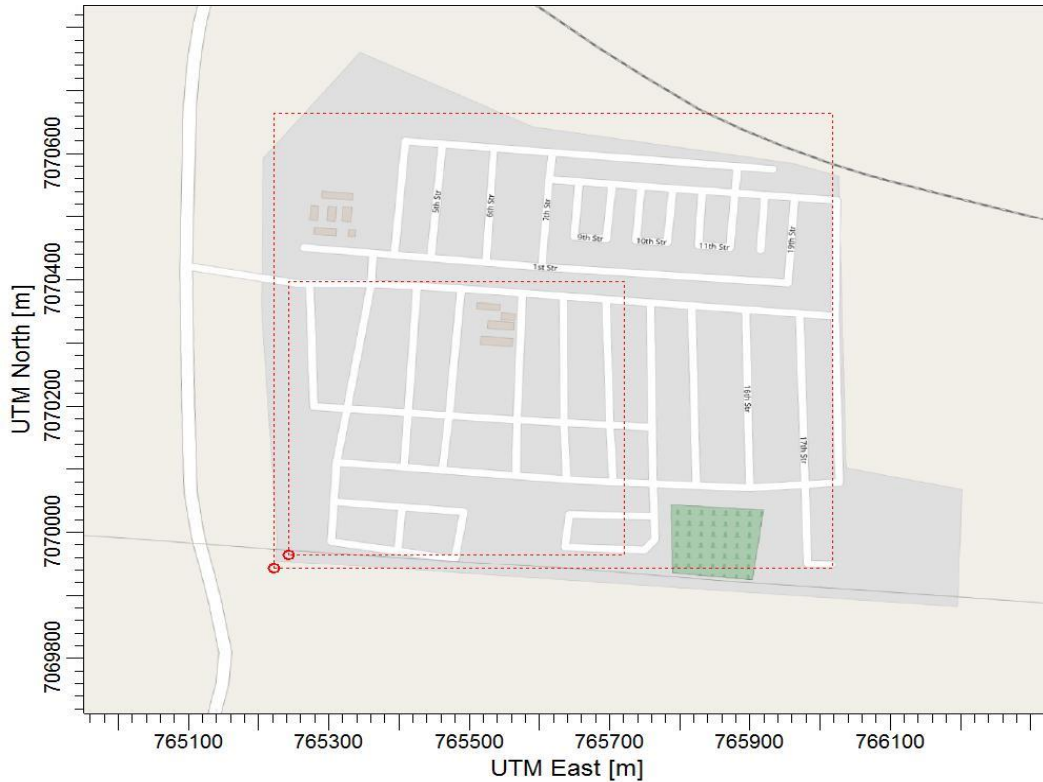


Figure 3-14. The two area sources representing all the houses contributing to domestic fuel burning as an area source (model run 1 (smaller area source) & model run 3 (larger area source)) as shown in Table 3-4 & Table 4-5 in Chapter 3

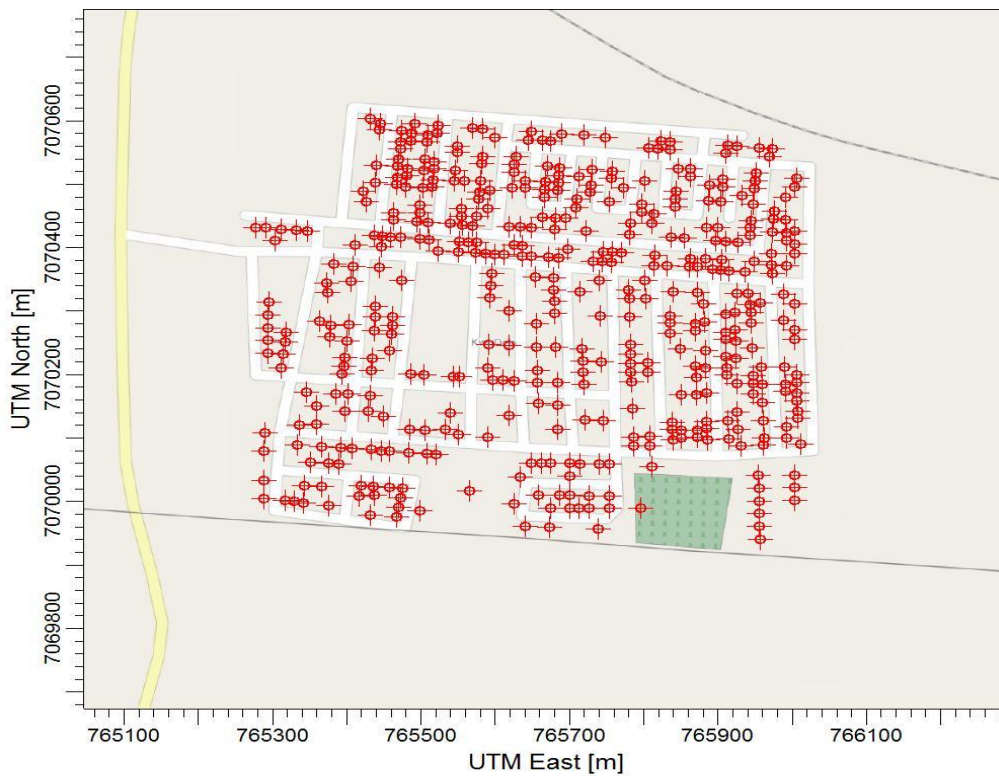


Figure 3-15. 456 point sources representing each house contributing to domestic fuel burning (model run 2, best case scenario as shown in Table 3-4 & Table 4-5 in Chapter 3)

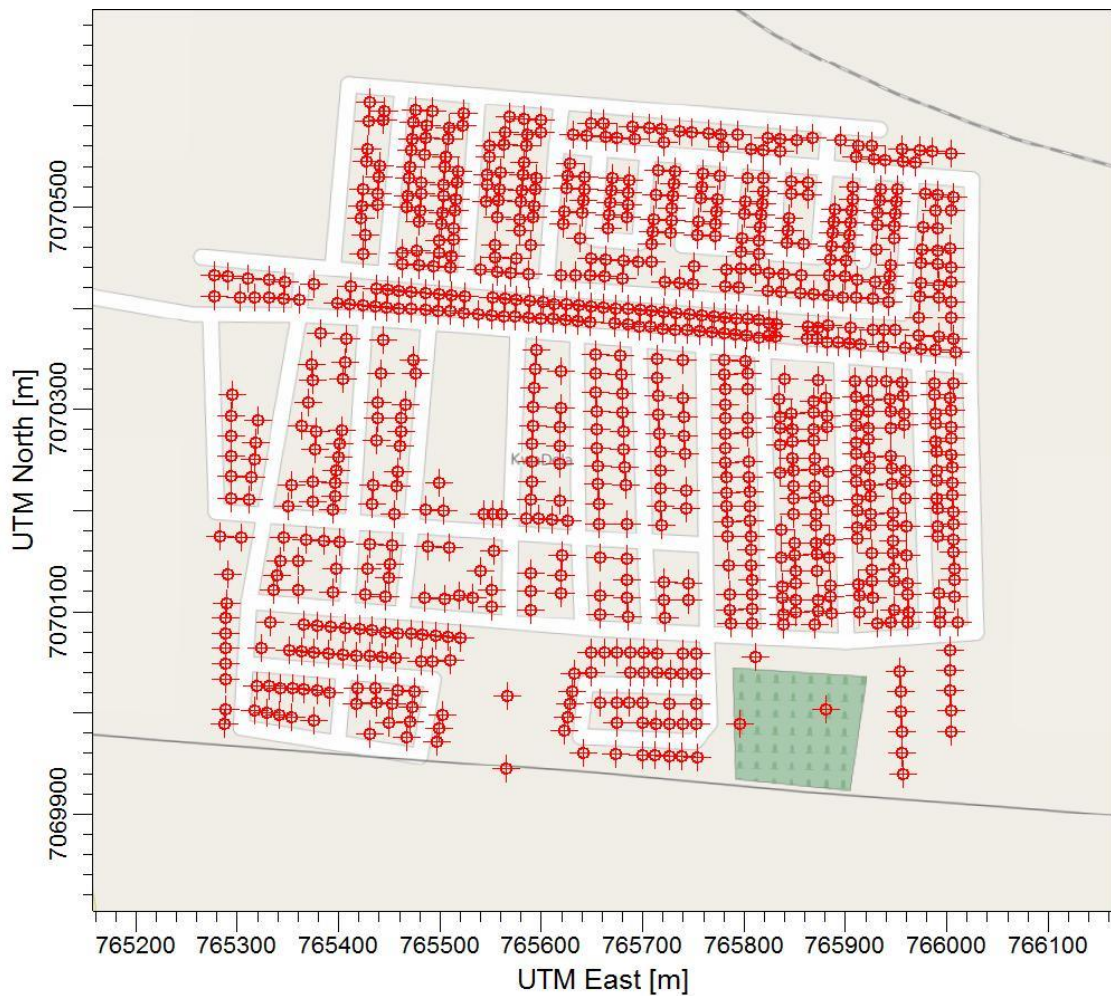


Figure 3-16. 833 point sources representing each house contributing to domestic fuel burning (model run 4, worst case scenario as shown in Table 3-4 & Table 4-5 in Chapter 3)

3.3.5 Model analysis

The four AERMOD model runs' results and the variability thereof are compared to each other to identify which inputs have the largest impact on the outputs. The two best-case scenarios (the lower extremities from Table 4-3) and two worst-case scenarios (the upper extremities from Table 4-3 in Chapter 3) have some similarities with one or two inputs being different causing the change in modelling results. This analysis indicates the different inputs to which the model is most sensitive to, depending on the variation in results as a cause of varying certain model inputs.

3.4 Modelling source contributions to ambient particulate matter (PM₁₀) in Kwadela, Mpumalanga

An AERMOD dispersion model was used to do one model run of four different pollution sources, three local sources: domestic fuel burning, windblown dust and waste burning and one other source: coal-fired industrial sources within a 50km radius of the study area. The small low-income settlement situated in Mpumalanga, Kwadela, discussed earlier in this chapter, was also used as the study area for this model run.

AERMOD performs better with short-range pollution distribution as mentioned before, and as this modelling scenario only modelled pollution distributions in a range of 50km and less, it was chosen. AERMOD is not necessarily the only dispersion model appropriate for short-range modelling scenarios, but being the US EPA's suggested dispersion model, for this case study AERMOD was the preferred choice.

3.4.1 Model set-up

The AERMET processor was run with the following data and the output as shown in Figure 3-17 and Table 3-5 was used to set up AERMOD for the for the model run. Thereafter, the receptors were chosen, and all the other calculations concerning the source inputs are discussed in the next section called 'source characterisation'.

3.4.2 Meteorology data of Kwadela, Mpumalanga

Hourly data collected from available onsite data, from ERA-Interim and where missing data occurred from Ermelo (nr. "0479870 X" -26.50, 29.98) and Bethal (nr. "0478808 7" -26.462, 29.46) for the period 1 July until 30 September 2013 was used, focusing on the following parameters: temperature, pressure, wind direction, wind speed, rainfall and relative humidity. Three-hourly observations gathered by the Ermelo weather office were used to determine cloud base, cloud type and total cloud coverage. The most recent available climate statistics (such as the WB40 tables) for Ermelo and Bethal were also used. Figure 3-17 displays the meteorology conditions around Kwadela in 2013 (1 Jul to 30 Sep) and Table 3-5 outlines the detailed weather information.

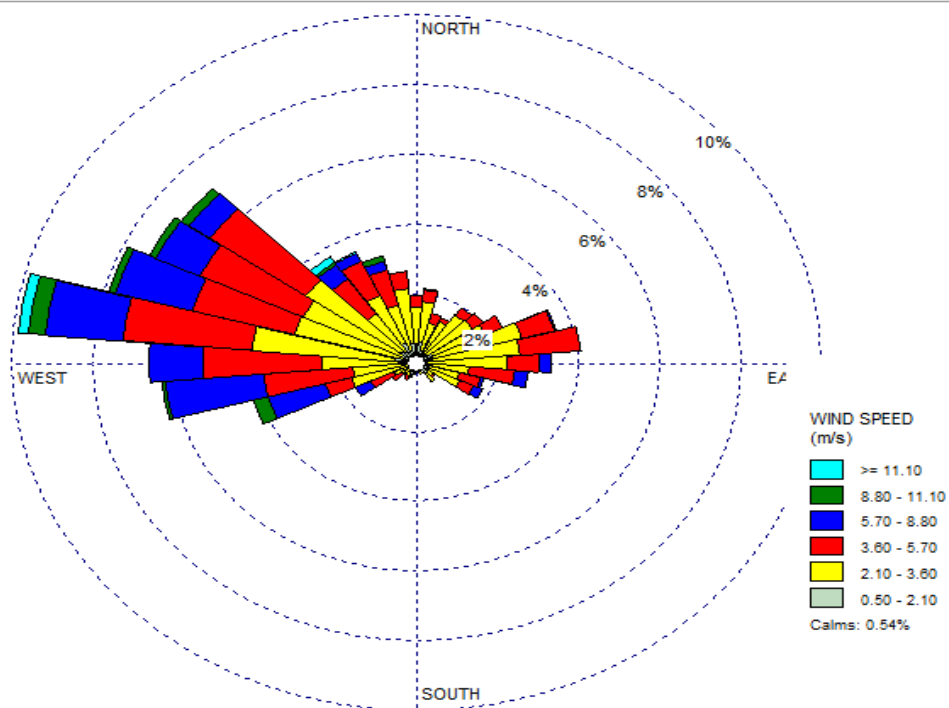


Figure 3-17. Wind rose of meteorology conditions around Kwadela in 2013 (1 Jul to 30 Sep)

Table 3-5: AERMET data file information

Years	2013
Total no. of hours	2208
Average wind speed	3.8 m/s
Calm records	12
Calm winds frequency	0.54%

3.4.3 Receptors used for the model run

The site-domain and terrain contours remained the same as referred to in the previous model set-up as the study area remained the same (Figure 3-5). A Cartesian receptor grid of 2 500 receptors (Figure 22) was also used for this model run as with the previous model set-up and with only one discrete receptor (Figure 3-18) placed in the same location as the caravan that was used in the Kwadela Ambient Air Quality Monitoring Campaign where the bulk of the ambient air quality measurements were made at the mobile monitoring station (Figure 3-25). This discrete receptor (Figure 3-18) enabled the comparison of monitored and modelled results evaluating the model's performance.



Figure 3-18. Terrain contours of Kwadela and the discrete receptor placed at the caravan monitoring site

3.4.4 Source characterisation

Each source's emission rate was calculated separately as they all have different calculation procedures and are discussed in this section individually. In AERMOD, the model run was done using the 'source groups' modelling option in order to distinguish between each separate source's emission contribution as well as the total emission concentrations. This also displays how dispersion models can be used to measure the different source contributions.

In Kwadela, domestic fuel burning, waste burning and windblown dust are categorised as the main contributing PM air pollution sources. These three sources are classified as local sources. Traffic emissions were not considered as this is a small low-income settlement with very few vehicles in the area; however, in a large urban settlement, vehicle emissions will definitely need to be considered. Lastly, the surrounding industrial emissions (50km radius) were also added as a main contributing source, classified as an 'other source', as opposed to local sources. Some arguments state that industrial sources make a larger contribution to local urban air quality than both modelled and monitored results show. Modelling these sources has given clarity on this matter and the importance of each source, as can be seen clearly in the case of Kwadela, where there are relatively few other pollution sources in the surrounding area; this in contrast to most urban environments that are affected by multiple sources of pollution. The modelling results implied which air pollution source made the greatest contribution causing poor ambient air quality.

3.4.4.1 Domestic fuel burning

The emission calculation formula used for domestic fuel burning was similar to that of the previous section; however ‘worst case’ and ‘best case’ scenarios were used, whereas for the model run in this section is more realistic and ‘medium’ emissions calculation was done.

The total number of houses considered to emit was 603 (Figure 3-19), with an emission rate of 0.001385g/s per house. The emissions from domestic burning were quantified using a combination of census data, in-stack monitoring, and detailed coal surveys done as part of the Kwadela Ambient Air Quality Monitoring Campaign study as shown in Table 3-6.

Table 3-6: Domestic fuel burning emission calculations (PM₁₀)

Fuel			Unit
Coal	Emission factor	12 ^a	g/kg
	Activity rate	3.65	ton/year
	Number of households	585	number
	Emission rate	0.8125	g/s
Wood	Emission factor	17.3 ^b	g/kg
	Activity rate	4.56	ton/year
	Number of households	9	number
	Emission rate	0.0225	g/s
Paraffin	Emission factor	0.2 ^{c,d}	g/kg
	Activity rate	0.17	ton/year
	Number of households	3	Number
	Emission rate	0.0	g/s
LPG	Emission factor	0.2 ^d	g/kg
	Activity rate	0.0057	ton/year
	Number of households	6	Number
	Emission rate	0.0	g/s
Total emission rate (ER)		0.8350	g/s
Total emission rate (ER) for each point source		0.0014	g/s

a) Scorgie (2012)

b) Cambridge Environmental Consultants (2010)

c) Scorgie (2004)

d) EPA (US) (2000)

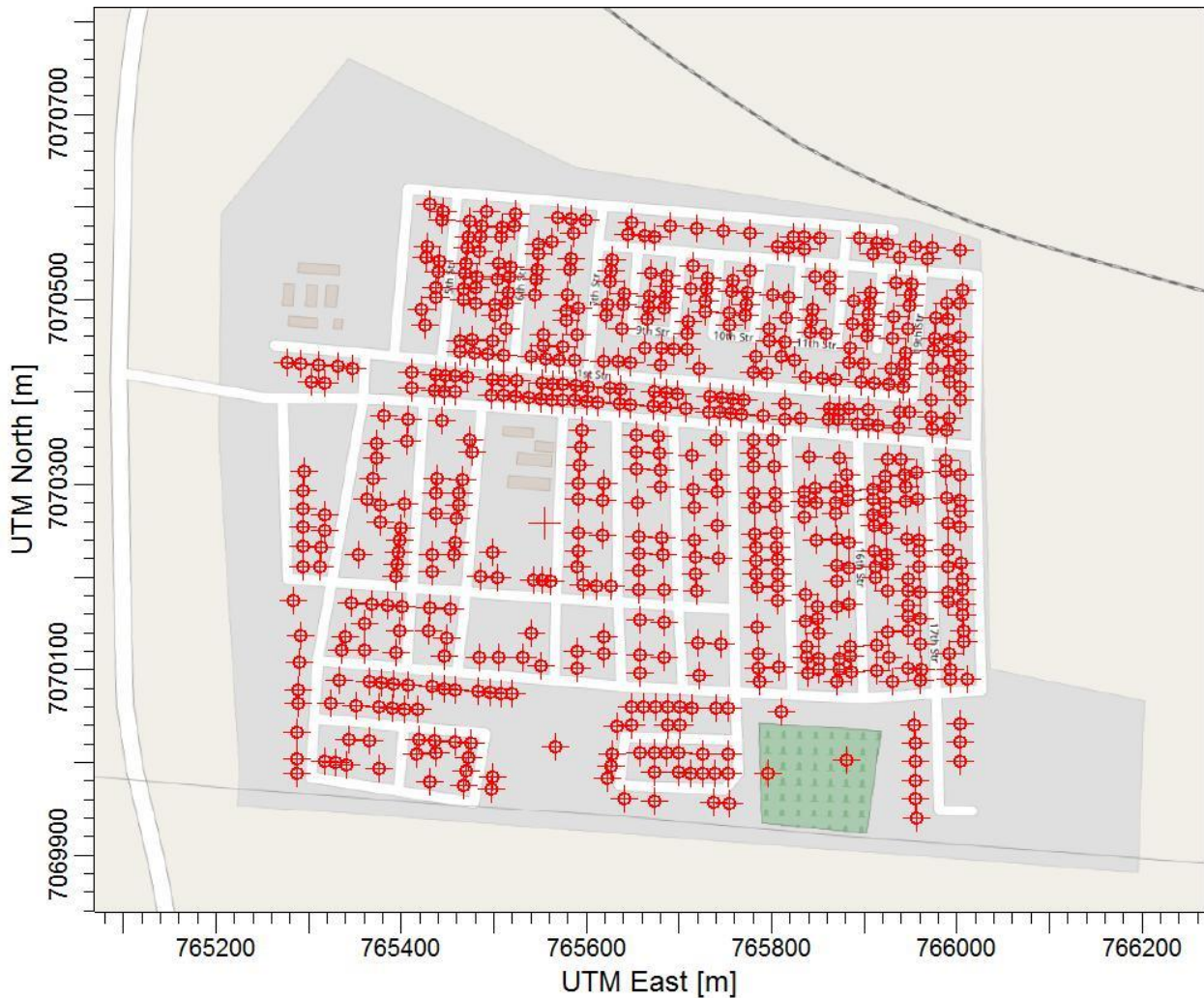


Figure 3-19. 603 point sources representing each house contributing to domestic fuel burning

3.4.4.2 Windblown dust

The emission calculation method of Korcz *et al.* (2009) was used for windblown dust. The soil of Kwadela was classified as fine unstable soil and consists 60% of Kwadela's total surface. The land type is classified more specifically as prism cutanic and/or pedocutanic diagnostic dominant horizons, vertic, malonic, and red structured. Windblown dust was represented as one area source with a land area of 344 314.65m² (Figure 3-20). The area representing windblown dust does not cover the whole of Kwadela, but as the area of the dust reservoir reduced by a factor of vegetation cover. The final emission rate used as input for the model is 0.0000058g/s/m² (vertical emission rate x horizontal emissions rate)/s).

The vertical emission rate was classified as 'urban unstable', which is 1. The horizontal emission rate was calculated as follows:

$$ER = \{ \text{land area, m}^2 \} \\ \times \{ [\text{spike emission factor, g/s}^{-2}] \\ + [(\text{duration of erosion event, h}) \\ \times (\text{emission factor, g/m}^2\text{h}^{-1})] \}$$

where:

- Erosion event is a period of time that meteorological parameters enable erosion (1h or 10h, depending on the surface stability) = 1 hour.
- Land area is the area of the dust reservoir reduced by a factor of vegetation cover = 344314.6531m².
- Spike emission factor (Table 3-7) emission factor (Table 3-8):

Table 3-7: Spike emission factor

	8.9–	11.1–	13.4–	15.6–	17.8–	20–	22.3–
Wind speed	11.1	13.4	15.6	17.8	20.0	22.3	24.5
Unstable fine soil	0.393	0.334	0.797	0.582	1.574	1.435	1.872

Table 3-8: Emission factor

	8.9–	11.1–	13.4–	15.6–	17.8–	20–	22.3–
Wind speed	11.1	13.4	15.6	17.8	20.0	22.3	24.5
Unstable fine soil	2.142	2.632	1.917	2.923	4.689	4.068	4.5



Figure 3-20. Windblown dust as one area source with a total area of 344314.6531m²

3.4.4.3 Waste burning

Waste burning had some complications as the census data was taken into consideration for the emission calculations, but the reality seen in Kwadela did not correlate with the census data. The census data recorded only 15% of the total waste not being removed by public services, but in Kwadela there were a number of waste burning dumps (Figure 3-22).

The income level of Kwadela had to be determined so that the waste per person per day could be calculated and, according to Fisher and Sánchez Piña (2013), Kwadela falls into the “very low and low income” class, making the average waste per person per day 0.41kg/day. Secondly, an emission factor for waste burning was used from the US EPA’s AP42, being 8g/kg and the total land cover of Kwadela is 573 857.75m² being the size of the area source representing waste burning (Figure 3-21).

Two calculations were needed to calculate the emission rate for waste burning (US EPA’s AP42):

(1) Total waste burned (kg/day) = people burning waste x waste per person (kg/person/day)
 3708 x 0.41 (kg/person/day)
 1520.28 (kg/day)

(2) PM₁₀ emission rate (g/s) = Emission Factor (EF) x total waste burned (kg/day)
 8 (g/kg) x 1520.28 (kg/day)
 12162.24 (kg/day)
 (12162.24/1000)/(24*60*60) (g/s)
 0.000140767 (g/s)
 0.00000000025 (g/s/m²)



Figure 3-21. Waste Burning as one area source with a total area of 573857m²



Figure 3-22. Waste burning dump in Kwadela

3.4.4.4 Industries

Lastly, there were four industrial power stations within a 50km radius of Kwadela (Figure 3-23 & Figure 3-24), namely Camden, Hendrina, Komati and Tutuka, each with their own unique emission rates, as seen in Table 3-9.

Table 3-9: Surrounding industrial power stations' emission information (Pretorius *et al.*, 2015)

Power station	Position (longitude; latitude)		Stack height (m)	Effective stack diameter (m)	Flow rate (m/s)	Exit temperature (K)	PM₁₀ (g/s)	PM₁₀ (t/ya)
Camden	-26.62	30.091	155	17	14	423	41.2	1300
Hendrina	-26.031	29.601	155	16	22	411	28.8	910
Komati	-26.091	29.422	220	17	10	418	65.6	2070
Tutuka	-26.776	29.352	275	17	29	413	499.7	15770

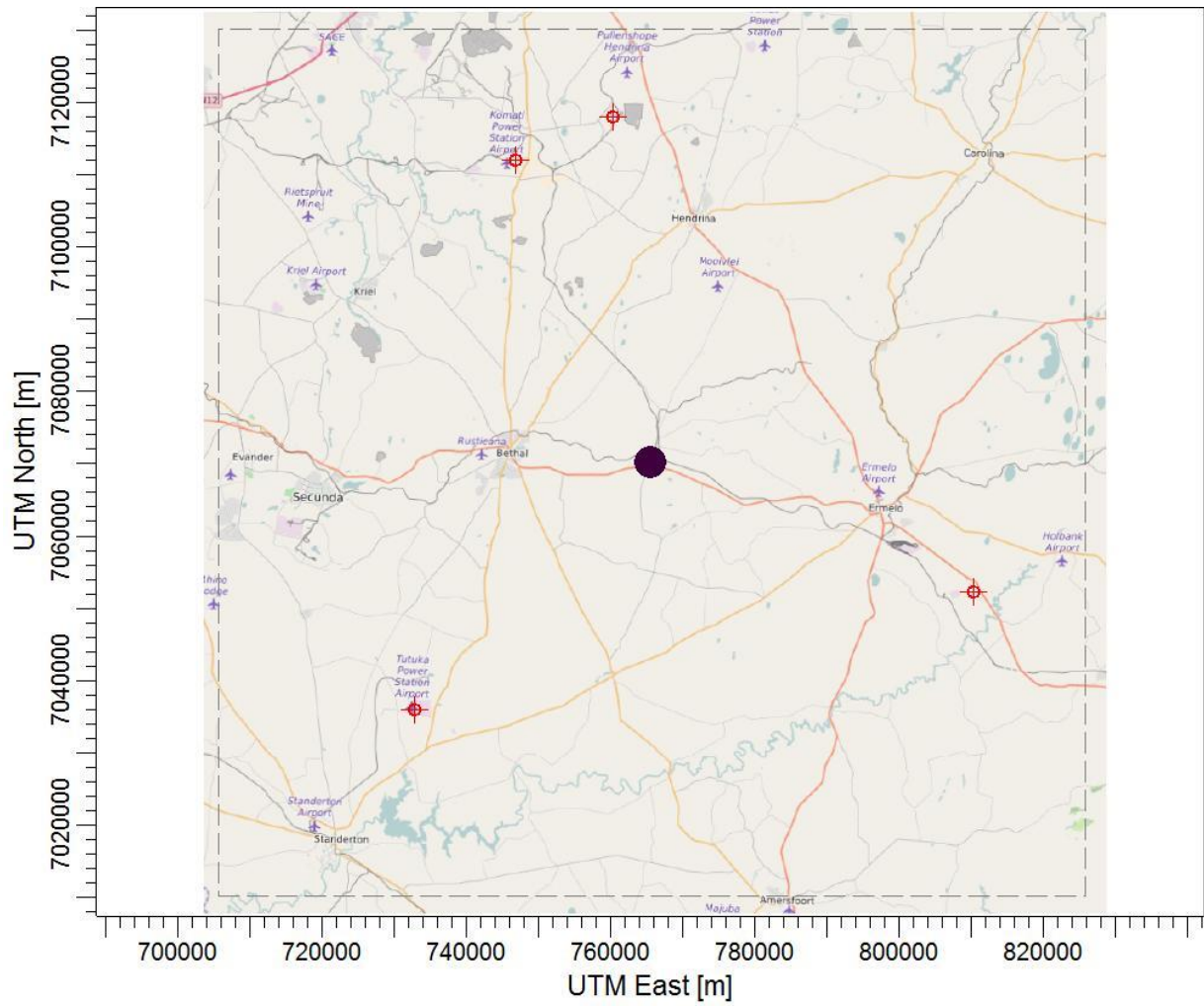


Figure 3-23. Power stations (represented as the red circles) modelled within a 50km radius from Kwadela (represented as the black circle)



Figure 3-24. Power stations within a 50km radius of Kwadela modelled as sources contributing to Kwadela’s ambient air quality (PM₁₀)

Table 3-10: Final emission rates of Chapter 4’s model run

Source	Emission rate	Unit	Source type
Domestic fuel burning	0.0014 (per point source)	g/s	603 point sources
Industry 1 (Camden PS)	41.2	g/s	point source
Industry 2 (Hendrina PS)	28.8	g/s	point source
Industry 3 (Komati PS)	65.5	g/s	point source
Industry 4 (Tutuka PS)	499.7	g/s	point source
Waste burning	0.0000000025	g/s/m ²	rectangular area
Dust	0.0000058	g/s/m ²	rectangular area

3.4.5 Source contributions evaluation

The contribution of each source is evaluated against the total concentrations modelled and then the one-hour average modelling results are compared to ambient measurements made during the winter Kwadela Ambient Air Quality Monitoring Campaign in 2013 to assess the model's performance and accuracy. This is shown in Chapter 4.

3.5 The Kwadela Ambient Air Quality Monitoring Campaign

An intensive air quality sampling campaign was conducted in Kwadela. The aim of this campaign was to quantify the air quality during winter in a domestic fuel burning community after an extensive programme was implemented to improve the thermal efficiency of houses. Ambient monitoring was conducted at three different sites in Kwadela: the main ambient monitoring site was located at the secondary school close to the centre of Kwadela, as seen in Figure 3-25, and two other ambient PM sites were located to the north-east and south-east. Twenty houses were arbitrarily chosen for indoor monitoring. The overall objective of the air quality monitoring component of the project was to determine (a) the baseline air quality in the pilot community, (b) the relative contribution of domestic fuel burning compared to other pollutant sources, and (c) the impact of changes in domestic fuel burning due to the retrofit intervention on ambient air quality in the pilot community.

Measurements were conducted from 7 July 2013 to 13 August 2013 for the first winter campaign, 10 February 2014 to 6 May 2014 for the first summer campaign, 7 July 2014 to 17 September 2014 for the second winter campaign and 11 February 2015 to 13 April 2015 as the second summer campaign. Ambient air quality was characterised by measuring SO₂, NO_x, O₃, CO, CO₂, BTEX (benzene, toluene, ethylbenzene and xylene), PM₁₀, PM_{2.5}, black carbon and meteorological conditions. Ambient air quality is poor during the winter in Kwadela. AAQs for PM₁₀ and PM_{2.5} are both exceeded. The 99th percentile of the daily averaged PM₁₀ is 96µg/m³ in summer and ranges between 162µg/m³ and 310µg/m³ during winter. During winter, the new (AAQS in force from Jan 2015) ambient PM₁₀ standards were exceeded at the main monitoring site more than 50% of the time. Judging by the diurnal profile of PM with peaks in the mornings and evenings, residential solid fuel burning is mainly responsible for these high ambient PM values. This is significant since Kwadela is a small settlement (fewer than 1 000 households) located +/- 45km from the nearest industrial source. This also implies that solid fuel for cooking purposes alone is enough to raise ambient PM levels to above air quality standards.

Data from all the different platforms was integrated into one coherent dataset with a temporal resolution of 1 minute. All the ambient variables were collected at the mobile monitoring station (located at 29.6635, -26.4633), except for the E-samples (E-sampler 1 located at 29.6623, -26.4626 and E-sampler 2 at 29.6626, -26.4649).

3.5.1 Site instrumentation

Horiba and Thermo Scientific Environmental Monitoring Instruments (analysers) were used to sample ambient concentrations of NO, NO₂, SO₂, CO₂, CO, and O₃ continuously in 1-minute average intervals and were recorded using various data acquisition systems. A summary of the equipment utilised to sample is given in Table 3-11. Calibration of each instrument was done before and after the campaign. The ambient gas analysers were housed in a mobile monitoring station and the air was pumped into the caravan (Figure 3-25) through Teflon tubing that was directed to each of the trace gas analysers; in addition to the trace gas instruments, two PM instruments were operated in the caravan for the duration of the campaign. Co-located was a fully automatic meteorological station equipped to measure wind speed and direction, solar radiation and temperature, humidity, atmospheric pressure and rainfall. These instruments also sampled meteorological data at 1-minute time intervals.



Figure 3-25. The mobile monitoring station where the bulk of the ambient air quality measurements were made

Table 3-11: Summary of instrumentation deployed for the Kwadela monitoring campaign

Parameter	Operating principle/ instrument model	Range	Precision	Sampling rate
Particulate matter				
PM ₁₀ concentrations	Horiba BAM 1020	0 to 10 mg/m ³	2.4 µg/m ³	60 min
PM ₁₀ concentrations	MetOne E-Sampler	0 to 1 mg/m ³	0.003 mg/m ³ or 2%	60 min
PM _{2.5} concentrations	MetOne E-Bam	0 to 65 mg/m ³	2.5 mg/m ³ or 10%	5 min
BC concentrations	Aetholometer 5012 MAAP-CBC	0 to 900 mg/m ³		2 min
Meteorology				
Temperature	Vaisala HMP60	-40°C to 60°C	± 0.6 °C	1 min
Humidity	Vaisala HMP60	0-100%	± 5%	1 min
Pressure	RM Young 61302	500-1100 hPa	0.3 hPa	1 min
Wind speed and direction	RM Young 05103	0-100 m/s	± 3m/s or 1%	1 min
Rainfall	RM Young 52203	0.1 mm per tip	2% to 3%	1 min
Solar radiation	LI-COR LI-200 pyranometer	0 W/m ² to 3000 W/m ²	± 5%	1 min

3.5.2 Monitored results

In this campaign, it was confirmed that PM is the pollutant of most concern in low-income settlements; it not only indicated the largest impact on health, but also had the highest recorded levels relative to the ambient standards. A total of 633 hours of PM₁₀ data was collected. Additional datasets of 803 and 710 hours of PM₁₀ data respectively were collected at two additional ambient sites. The 99th percentile of PM₁₀ and PM_{2.5} exceeds the new stricter AAQS that came into force 1 January 2015. The median of the daily average PM₁₀ values is ±107 µg/m³ and exceeds the daily ambient standard. Hourly PM₁₀ levels are higher than the new ambient standards 50% of the time during winter. The spatial variability of the three PM₁₀ measurements is significant: the maximum measurement of PM₁₀ was 447 µg/m³ (1-hour average) for the BAM 1020 and 1840 µg/m³ and 1169 µg/m³ for the two E-samplers, respectively. The daily levels vary slightly less, indicating 24-hour averages of between 38 µg/m³ and 302 µg/m³. The variability of the upper quartile (highest 25% of the data) is slightly lower. This corresponds to the view that ambient air quality in a domestic fuel burning settlement is made up of many point sources. While some areas might have lower levels of PM on average, the maximum levels are associated with peak events. The high PM-levels

demonstrate that even small settlements have ambient concentrations well above the limit set by AAQS (Table 3-12).

Table 3-12: Statistics for ambient PM measurements during the 2013 winter campaign

	BC $\mu\text{g}/\text{m}^3$	PM_{2.5} $\mu\text{g}/\text{m}^3$	PM₁₀ $\mu\text{g}/\text{m}^3$	E-sampler 1 $\mu\text{g}/\text{m}^3$	E-sampler 2 $\mu\text{g}/\text{m}^3$
hourly averages					
Measurements	1555	1004	1805	1176	442
Average	0.6	19.3	51.9	15.8	23.7
Standard deviation	0.7	20.3	31.3	23.1	40.8
25 th percentile	0.2	9.0	30.5	3.9	2.0
Median	0.4	16.9	44.8	8.9	7.0
75 th percentile	0.7	24.1	66.3	17.8	27.5
99 th percentile	3.9	107.2	159.4	133.9	215.1
Maximum	7.8	306.8	325.2	241.7	298.2
24-hour averages					
Measurements	74	47	79	56	24
Average	0.7	20.2	51.8	16.0	24.1
Standard deviation	0.3	13.7	17.6	9.3	17.5
25 th percentile	0.5	14.1	39.7	8.7	6.6
Median	0.6	19.1	47.9	15.2	27.7
75 th percentile	0.7	24.1	64.3	21.5	36.7
99 th percentile	1.7	60.1	95.6	40.5	59.6
Maximum	1.9	67.9	101.4	45.8	61.7
Exceedances		9	23	8	4

3.6 Chapter conclusion

The study area's small population size simplifies the data and methods of this study compared to large datasets, especially for objectives 3 and 4 when simulating the air quality of Kwadela. However, there were still a few challenges concerning the data and methods: 1) the guidelines on how the model set-up should look like for modelling intra-urban air quality, 2) the variability of the available data to use for the emission factors to calculate the emission rates, 3) how each source should be presented as in the model, e.g. an area or point source, 4) how to account for each household's different fuel type, fuel amount, burning times and durations, and 5) the census data for waste burning in Kwadela was not accurate, but was used as the most reliable source of data available. Even in this simplified study, the complexity of modelling intra-urban air quality is evident.

4. CHALLENGES IN MODELLING INTRA-URBAN AIR QUALITY IN THE SOUTHERN AFRICAN CONTEXT

Introduction

In this chapter, the focus will be on the first two objectives, (1) characterising the ambient PM loading and variability of five low-income urban areas on the South African Highveld, and (2) evaluating the sensitivity of simulated ambient PM to model inputs in Kwadela, Mpumalanga, by comparing different dispersion modelling scenarios.

4.1 Characterising the ambient particulate matter loading and variability of five low-income urban areas on the South African Highveld

In SA, increasing urban development is a common trend, especially inter-provincial migration where South Africans 'follow the money', moving to bigger and better cities, with Gauteng being the economic hub of the country. This makes the poor air quality and its health impacts in urban settlements very relevant to the South African context as people live and breathe this polluted air on a daily basis (Christopher, 2014). Domestic fuel burning in urban areas is one of South Africa's biggest sources contributing to PM levels (Scorgie, 2009), as it is used for crucial day-to-day purposes such as space heating and cooking (Engelbrecht *et al.*, 2002). To worsen the air pollution, coal is easily accessible and inexpensive (Snyman & Botha, 2003). Fossil fuel combustion emissions and traffic-related air pollution target public health in South African urban settlements (Norman *et al.*, 2007; Scorgie, 2012). It is difficult to quantify the impact of air pollution because of the lack of available information on exposure of the population to air pollutants. Unfortunately, in a developing country such as South Africa, effective air quality management will remain a challenge because of its dependence on coal for cooking and heating purposes, industrial activity and mining sectors.

4.1.1 *Kwadela and four additional low-income urban settlements' daily and diurnal PM₁₀ concentrations*

Kwadela and four additional low-income settlements were considered in order to characterise the intra-urban ambient air quality of South African low-income urban settlements. Table 4-1 contains monitored ambient air quality results of PM₁₀ in some of South Africa's low-income settlements received from SAAQIS. The results for the other four settlements were dependent on the availability of data in the datasets from 2004 to 2010. Kwadela's results only include air quality monitored during the winter months of 2013, but measure higher in some cases than the other settlements. This leads to the assumption that the average measurements of the other settlements, if only measured during

winter, would be much higher than when all the seasons are included, as Kwadela is smaller in size and would mean less domestic fuel burning occurrences. The data displays some extremely high monitored hourly averaged concentrations compared to the NAAQS, especially Kwadela (winter of 2013) and Zamdela, as shown in Figure 4-1 and Figure 4-2.

Table 4-1: Hourly data (PM₁₀) comparisons of South African settlements between 2004 and 2010

Variable	Kwadela	Alexandra	Sebokeng	Zamdela	Sharpeville
Count	1091	41502	35523	27933	38537
Mean	103	49	54	94	82
Std	80	42	49	91	76
Min	4	1	0	0	1
25%	58	21	23	36	31
50%	85	40	41	68	60
75%	122	77	69	121	109
99%	435	191	240	443	350
Max	843	1393	881	1308	1495

Figure 4-1 and Figure 4-2 present the diurnals of PM₁₀ caused by domestic fuel burning of Kwadela and low-income settlements in Gauteng and the Free State. This displays the character and variability of ambient air quality conditions in typical low-income settlements in SA. The ambient air quality of urban settlements varies in space and time, but as seen in Figure 4-1 and Figure 4-2, they exceed the NAAQS daily, and should raise concerns. Peak concentrations are found in the mornings between 5am and 10pm and in the afternoon between 5pm and 10pm linking to the time for cooking and heating. Isolated high measurements are also present during midday. Kwadela's exceedances (Figure 4-1) are noticeably higher, being higher than the ambient standards 50% of the time during winter. Figure 4-3 displays the consistent presence of poor ambient air quality in these urban settlements, with only one out of four settlements not exceeding the daily NAAQS.

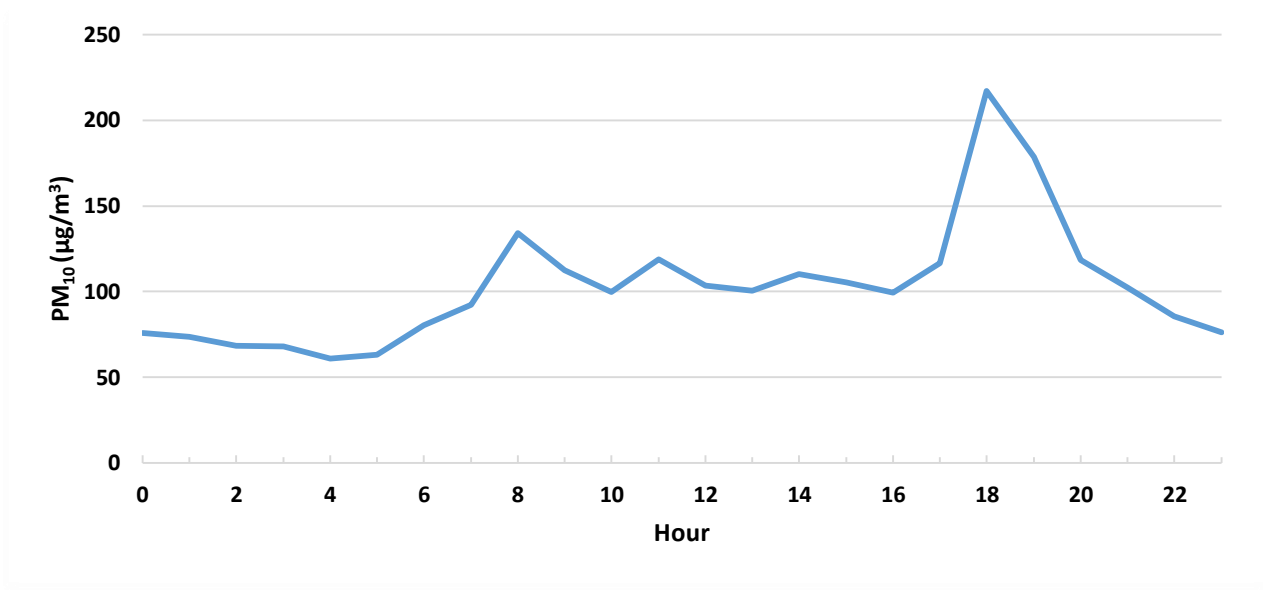


Figure 4-1. Hourly averaged data of Kwadela's intra-urban ambient air quality (PM₁₀) during winter, 2013

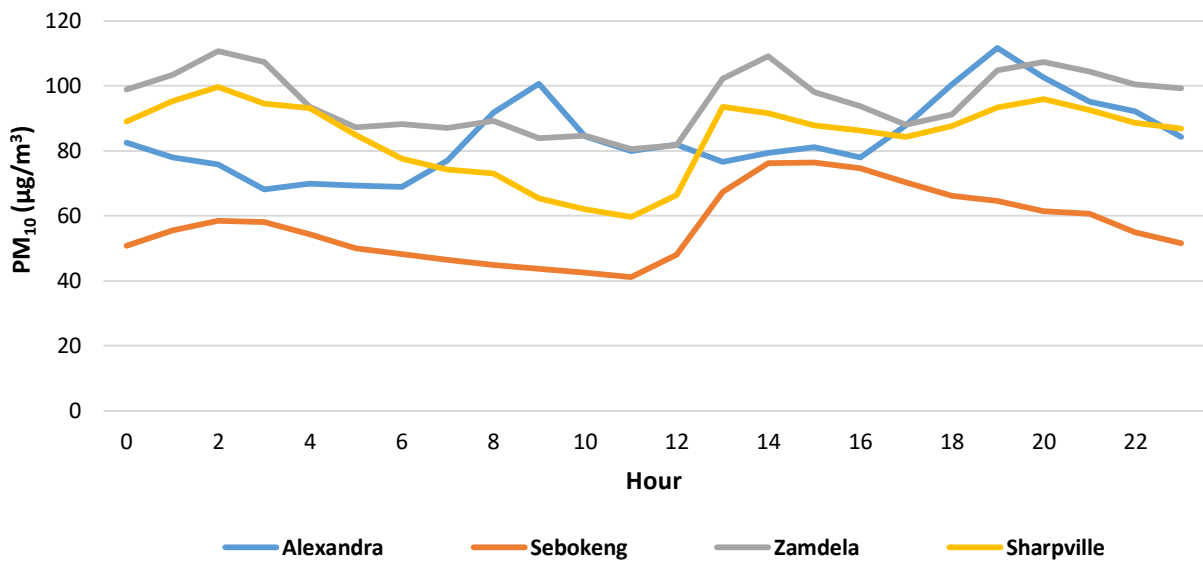


Figure 4-2. Hourly averaged data of intra-urban ambient air quality (PM₁₀) between 2004 and 2010 of four low-income settlements

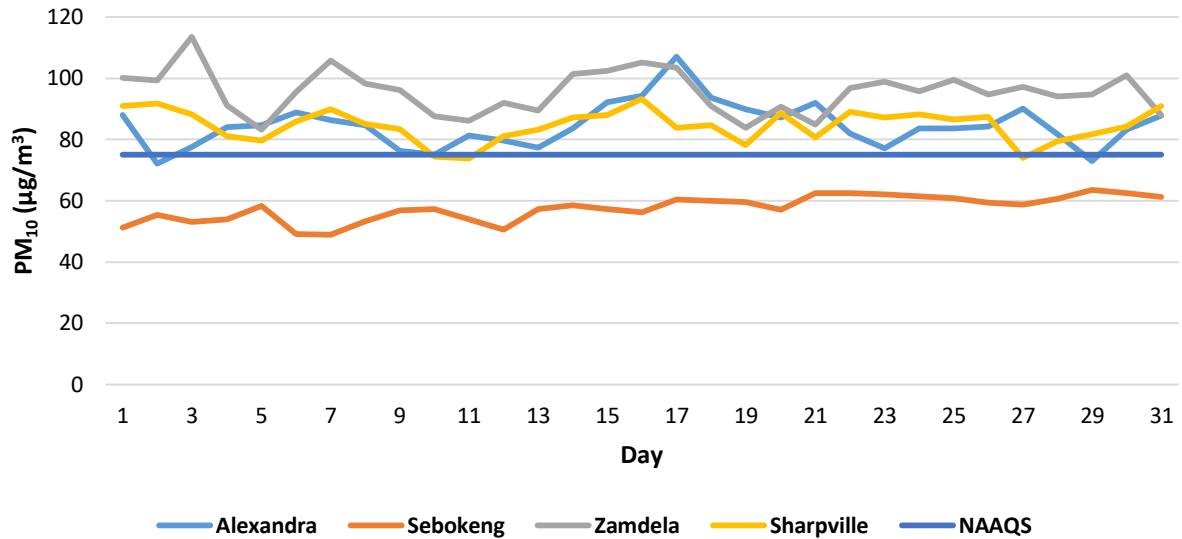


Figure 4-3. Daily averaged data of intra-urban ambient air quality (PM₁₀) between 2004 and 2010 of four low-income settlements

4.1.2 Four additional low-income urban settlements’ seasonal PM₁₀ concentrations

Seasonal percentiles are plotted of intra-urban ambient air quality (PM₁₀) between 2004 and 2010 of the same four low-income settlements in Gauteng and the Free State (Figure 4-4, Figure 4-5, Figure 4-6, Figure 4-7). In these figures, the highest measurements occur for the duration of winter. This justifies why Kwadela is monitored and modelled during the winter months, as this is when the highest levels relative to the ambient standards are recorded. Ambient air quality in solid fuel burning settlements is made up of many point sources. While some areas might have lower levels of PM on average, the maximum levels are associated with peak events and would be more similar. The high PM levels show that even small settlements have ambient concentrations well outside the NAAQS.

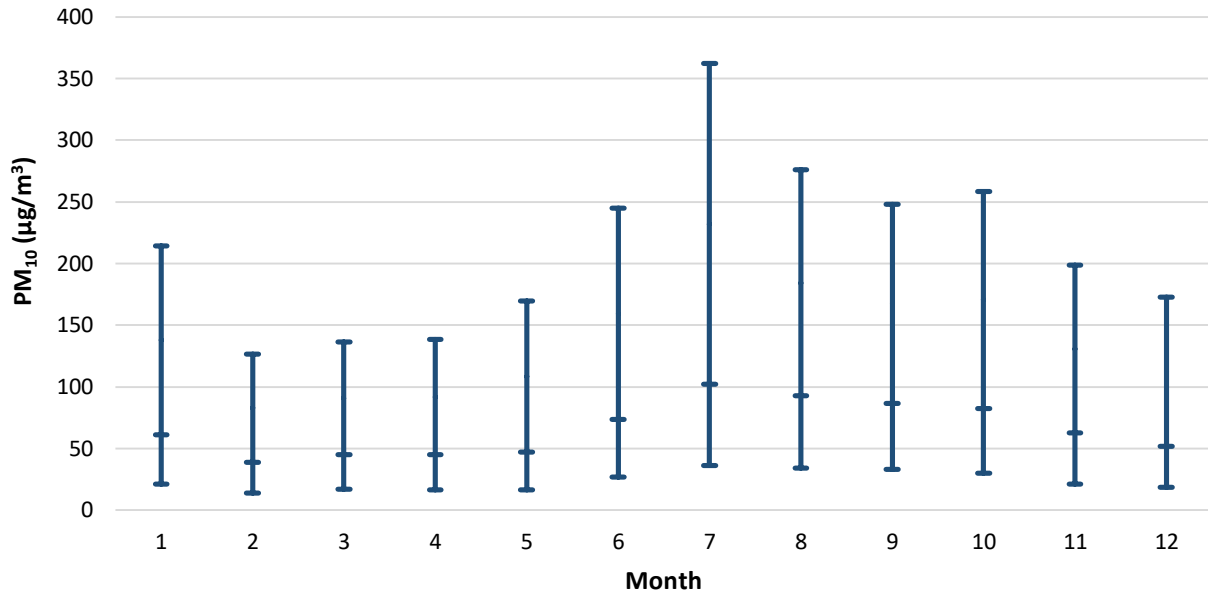


Figure 4-4. Box and whisker plot of the hourly average PM₁₀ of the month for Alexandra, Gauteng. The median (50th percentile) is shown by the middle bar and the whiskers indicate the 25th and 75th percentiles

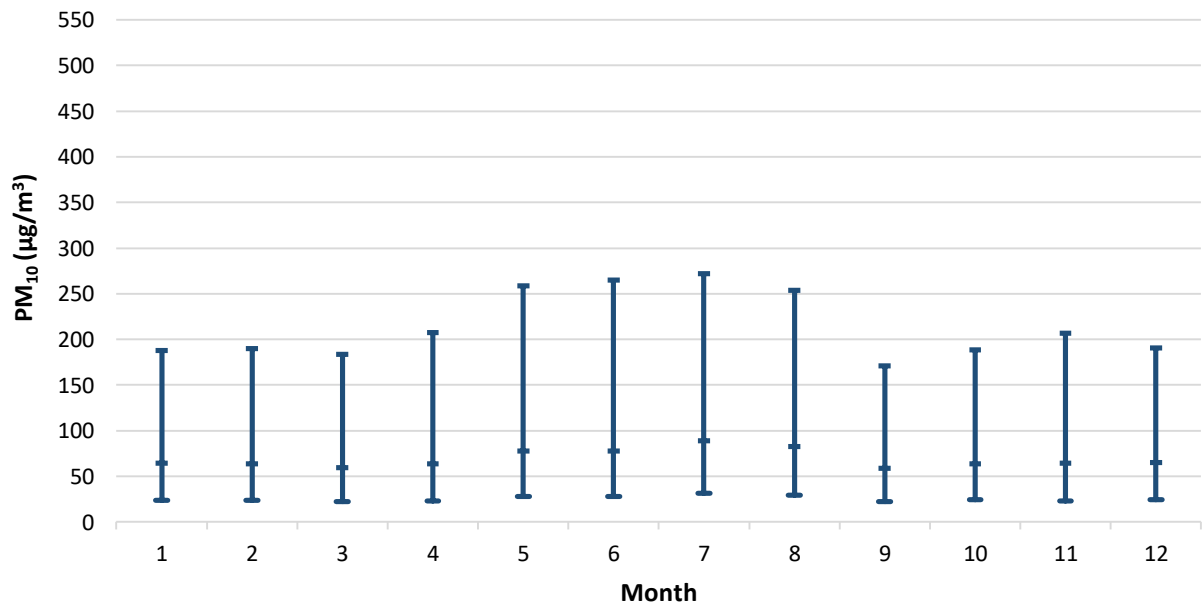


Figure 4-5. Box and whisker plot of the hourly average PM₁₀ of the month for Sebokeng, Gauteng. The median (50th percentile) is shown by the middle bar and the whiskers indicate the 25th and 75th percentiles

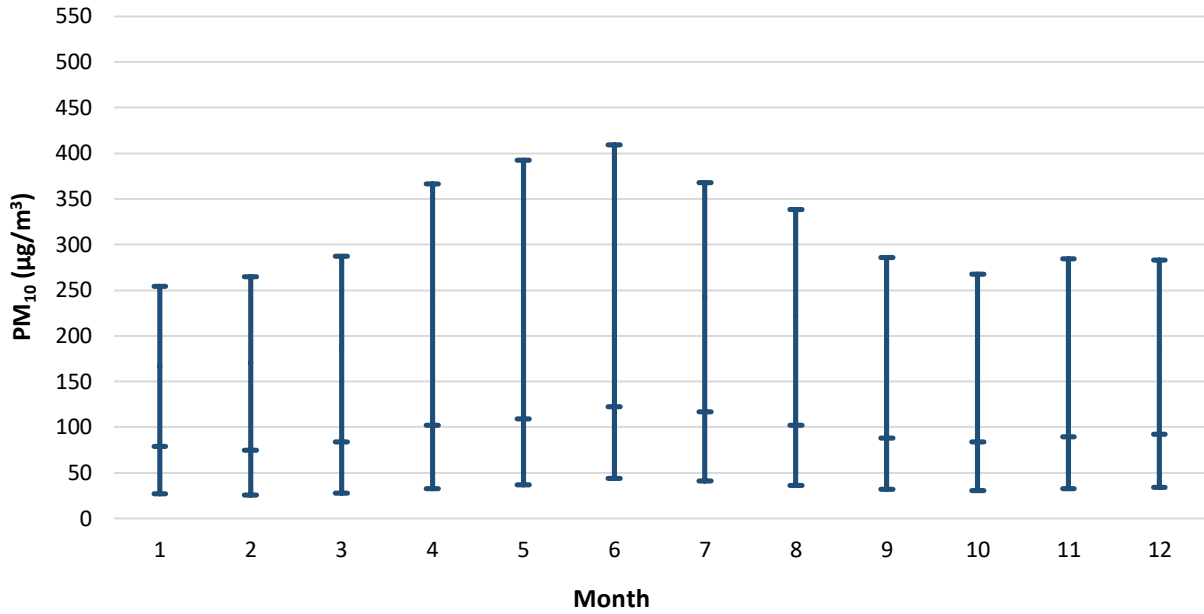


Figure 4-6. Box and whisker plot of the hourly average PM₁₀ of the month for Sharpeville, Gauteng. The median (50th percentile) is shown by the middle bar and the whiskers indicate the 25th and 75th percentiles

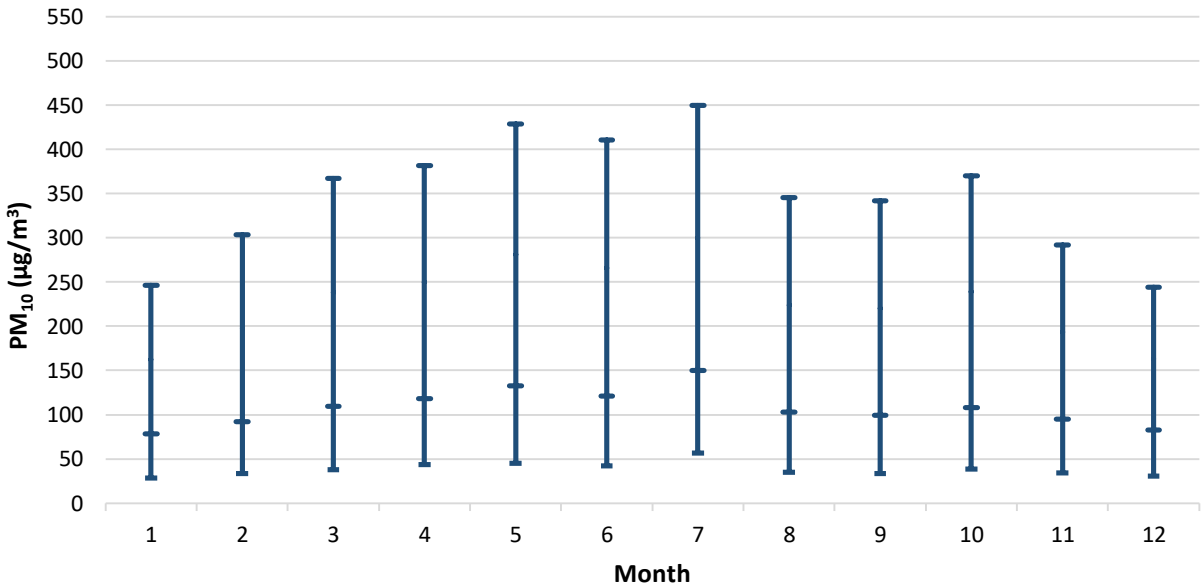


Figure 4-7. Box and whisker plot of the hourly average PM₁₀ of the month for Zamdela, Free State. The median (50th percentile) is shown by the middle bar and the whiskers indicate the 25th and 75th percentiles

Urban air pollution in SA is currently an important policy issue (DEA, 2006). The National Environmental Management: Air Quality Act 39 of 2004 states the objective of enhancing the quality of ambient air for the sake of securing an environment that is not harmful to the health and well-being of the people (Strydom & King, 2009:583). To achieve this objective, specifically in urban settlements regarding intra-urban ambient air quality, the process on exactly how to determine the concentrations of these pollutants still remains unclear. Therefore, before intra-urban ambient air quality can be regulated properly, the challenges accompanying the measurements of these pollutants must be understood.

4.2 Evaluating the sensitivity of simulated ambient particulate matter to model inputs

This evaluation indicates how the outputs vary when different inputs are provided and the impact that this has on the modelling results and concentration estimates given by the model.

Four AERMOD model runs were done on Kwadela, assuming best case and worst case scenarios as extremities with domestic fuel burning of the four dirty fuels described in Table 4-3 used as the source of pollution. Best case scenarios (the lower extreme values from Table 4-3) and worst case scenarios (the upper extreme values from Table 4-3) were used while varying the inputs as indicated in Table 4-4.

4.2.1 Results of the variability in available data for modelling intra-urban air quality in South Africa

Well-quantified source characteristics as part of modelling input are crucial. Table 4-2 and Table 4-3 display the variability of the current available data within the South African context, the range of data available and the lack thereof. Coal, wood, gas and paraffin were the combustion fuels focused on, as these are most commonly used in SA (van den Berg *et al.*, 2014). Accurate emission rates are crucial when modelling any inconsistent source, such as domestic fuel burning. It should be understood that being able to generate this kind of data, detailed studies must be done and the approach must be well justified. Studying Table 4-3, especially the emission factors for wood, there is a large variability, and the activity rates (AR) all have a large range of values available to use. The final emission rates (q) used as modelling input all have a large variability as a result of the previous range of values as well.

Table 4-2: Number of households in Kwadela using different domestic fuel burning in literature and census data

Literature source	Coal	Wood	Paraffin	LPG	Total households using domestic fuel burning
Census (2011)	453	9	3	6	n/a
Pauw (2008)	815	887	n/a	n/a	n/a
NOVA survey (2013)	758-809	n/a	n/a	n/a	797-844

*Pauw & Fisher stated that almost all the households use coal and/or wood, with 72 more households using wood.

Table 4-3: Variability in available source data for modelling intra-urban air quality in South Africa (PM₁₀)

Symbol	Description	Range of Values	Unit
EF _{wood}	Emission factor of wood	15.7 ^{a,b} –17.3 ^h	g/kg
EF _{coal}	Emission factor of coal	3.1 ^b –12 ⁱ	g/kg
EF _{paraffin}	Emission factor of paraffin	0.2 ^{a,b}	g/kg
EF _{LPG}	Emission factor of LPG gas	0.07 ⁱ –0.2 ^b	g/kg
AR _{wood}	Activity rate of wood	0.074 ^a –4.56 ^c	t/year
AR _{coal}	Activity rate of coal	0.224 ^a –3.65 ^{d,e,f,g}	t/year
AR _{paraffin}	Activity rate of paraffin	0.05 ^a –0.17 ⁱ	t/year
AR _{LPG}	Activity rate of LPG gas	0.0057 ⁱ	t/year
Q _{wood}	Emission rate of wood	0.000037–0.002514	g/s
Q _{coal}	Emission rate of coal	0.0099–1.1319	g/s
Q _{paraffin}	Emission rate of paraffin	0.0–0.000003	g/s
Q _{LPG}	Emission rate of LPG gas	0.0–0.000000217	g/s
Q _{DFB}	Emission rate of domestic fuel burning	0.01–1.154	g/s
t _h	Hourly time scale	1.000–1.125 ⁿ	scaling factor
t _m	Monthly time scale	0.601–0.577 ⁿ	scaling factor
S _{Type}	Source type	Area, Point	n/a
S _{Height}	Source release height	1.2–3	M
N _{householdsW}	Number of households using coal	453 ^k –815 ^l	Number
N _{householdsC}	Number of household using wood	9 ^k –887 ^l	Number
N _{householdsP}	Number of households using paraffin	1 ^m –3 ^k	Number
N _{householdsLPG}	Number of households using LPG	1 ^m –6 ^k	Number
a)	Scorgie (2004)		
b)	EPA (US) (2000)		
c)	Damm & Triebel (2008)		
d)	Mdluli (2007)		
e)	Naidoo (2014)		
f)	Piketh (2013)		
g)	Engelbrecht (2000)		
h)	Cambridge Environmental Research Consultants (2010)		
i)	Roberts & Wentzel (2006)		
j)	Scorgie (2012)		
k)	Census (2011)		
l)	Pauw (2008)		
m)	The assumption was made as it was possible that at least one house in Kwadela used that fuel for either cooking or heating		
n)	SAAQIS		

4.2.2 Emission rate calculations according to the findings in Table 4-3

As it is still unclear exactly how to model domestic fuel burning from residential areas on the intra-urban scale, the four different model runs and their results highlight the uncertainty and variability when modelling domestic fuel burning.

For model runs 1 and 2, the lowest figures considered in the literature (Table 4-3) were used for the calculations of the final emission rate (ER), called best case scenarios: 0.01g/s/m^2 and 0.000022g/s , respectively. For model runs 3 and 4, the highest figures found in the literature (Table 4-3) were used to calculate the emission rates (ER) termed worst case scenarios: 1.15g/s/m^2 and 0.0014g/s , respectively. The receptors for these model runs are outlined in section 3.3.3.

Firstly, the number of households needed to be established. It should be noted that in Table 4-2 Pauw (2008) stated that almost all households use coal or/and wood as a domestic fuel, but for the calculations the minimum households to use wood was assumed to be at least one and the maximum number of households were nine, being what the Census (2011) stated. This assumption was made so that the emissions will not be overestimated, as it is not clear when the households use either wood or coal or both, and therefore coal was used to represent the fuel for most of the households. This was done in Table 4-2, which was multiplied with the activity rates considered in the current literature in Table 4-3 and then finally multiplied with the various emission factors provided in the literature (Table 4-3). To calculate the different ER from area source to point sources, the area's final ER is divided by the number of houses in the area and given as input each as a separate point source. These calculations are outlined in Table 4-4.

Table 4-4: Emission calculations for domestic fuel burning

Dirty fuel		Min (best case)	Max (worst case)	Unit
Coal	Emission factor	3.1	12	g/kg
	Activity rate	0.22	3.65	ton/year
	Number of households	453	815	Number
	Emission rate	0.01	1.13	g/s
Wood	Emission factor	15.7	17.3	g/kg
	Activity rate	0.07	4.56	ton/year
	Number of households	1	9	Number
	Emission rate	0.00	0.02	g/s
Paraffin	Emission factor	0.2	0.2	g/kg
	Activity rate	0.05	0.17	ton/year
	Number of households	1	3	Number
	Emission rate	0.00	0.00	g/s
LPG	Emission factor	0.07	0.2	g/kg
	Activity rate	0.01	0.01	ton/year
	Number of households	1	6	Number
	Emission rate	0.00	0.00	g/s
Total emission rate (ER) (area source)		0.01	1.15	g/s
Total emission rate (ER) (point sources)		0.000022	0.0014	g/s

Table 4-5: Final emission rate inputs for each model run

Model run	ER	Unit	Source type
1 (best case, area source)	0.01	g/(s-m ²)	1 area (456 houses)
2 (best case, point sources)	0.000022	g/s	456 point sources
3 (worst case, area source)	1.15	g/(s-m ²)	1 area (833 houses)
4 (worst case, point sources)	0.0014	g/s	833 point sources

4.2.3 Results of the evaluation of the sensitivity of simulated ambient particulate matter to model inputs in Kwadela, Mpumalanga

Model run 4 was most closely related to the realistic scenario of the NOVA survey done in 2013 and also had the highest measured modelling results.

Therefore, by evaluating the variability of different inputs, it can clearly be seen that input variability greatly impacts the output. Table 4-6 and Figure 4-8 display this, as the concentrations measured by the model vary distinctively, although in the cases where an area or point source was chosen, the results tend to be more similar. It can be concluded that the typical air quality in South African urban environments is poor and exceeds the NAAQS various times as shown in Figure 4-3. The atmospheric environment is highly variable in space and time and this makes accurate modelling of these scenarios tedious and great care must be taken when choosing inputs and interpreting outputs.

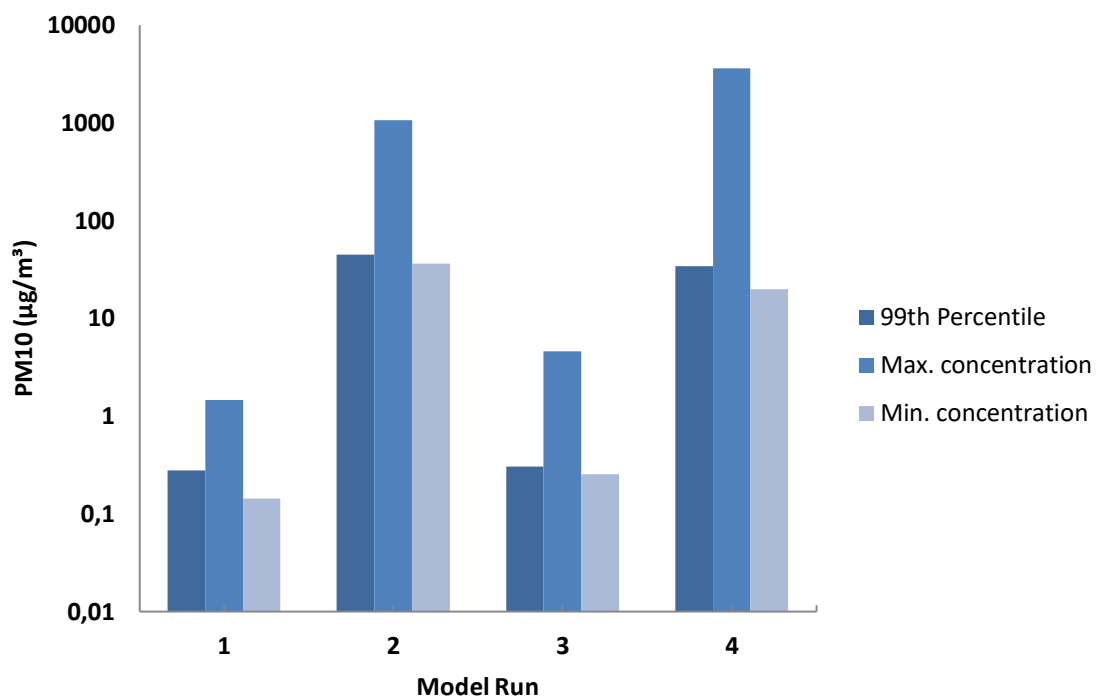


Figure 4-8. Evaluation of the sensitivity of simulated ambient particulate matter results of four model runs with different inputs

To conclude, changing the ER and the type of source, e.g. point sources or area source, made the largest impact on the results. In model runs 1 and 3, domestic fuel burning was represented as an area source, being Kwadela as a whole and the concentrations measured were significantly different than model runs 2 and 4, where domestic fuel burning was represented as point sources, each a household in the settlement with a different ER, also making a large impact on the output.

4.3 Chapter conclusion

Table 4-6: Evaluation of the sensitivity of simulated ambient particulate matter results of four model runs with different inputs

Variable	Model run 1	Model run 2	Model run 3	Model run 4
best/worst case	best case	best case	worst case	worst case
min concentration in $\mu\text{g}/\text{m}^3$	0.3	34.4	0.3	34.1
max concentration in $\mu\text{g}/\text{m}^3$	1.5	1056.4	4.6	3620.8
average concentration in $\mu\text{g}/\text{m}^3$ (4 th highest 24hour values)	0.1	36.4	0.3	19.8
24hour exceedances, threshold of 75 $\mu\text{g}/\text{m}^3$ (count)	1	133	1	168

In this chapter, the first two objectives were addressed as the typical ambient PM concentrations in low-income settlements were characterised and the sensitivity of simulated ambient PM to model inputs in Kwadela, Mpumalanga, by comparing different dispersion modelling scenarios, was evaluated. For optimal model output of dispersion models, high quality input is absolutely crucial (Pielke & Uliasz, 1998). When using dispersion models, there are countless input options influencing the output, contributing to the variability as well as the possibility of errors to occur for each modelling scenario. Minor changes in these variables may distress the distance within which concentration restrictions are surpassed by several hundred meters. This emphasises the importance of well-estimated input data to be used when modelling intra-urban air pollution.

Secondly, this illustrates the urgent need for strict guidelines on how these scenarios should be approached and modelled. It is so unfortunate that using these dispersion models as a tool for regulatory purposes has difficulty determining the air pollution levels in an environment that directly impacts the daily health of the population in developing countries such as South Africa, because of the variation in input parameters. It should be noted that regulatory instruments' focus is on industries and other less complex scenarios that can be grasped and influenced fairly easily. Emissions caused by intra-urban sources, especially low-income settlements, are exceptionally difficult to monitor, measure and model, causing even more challenges when applying constructive management in reality.

Gaussian dispersion models are therefore not the perfect tool to use when analysing intra-urban air pollution; however, realising how complicated the challenges are, the significance of the quality of the data being used and the need to model intra-urban centres' air quality validate using the AERMOD dispersion model for these simulations. This being said, when using Gaussian dispersion models, input data should be handled with great caution and accuracy, especially emission rates and the source type chosen to represent the source, as variability in these two inputs had the largest influence on the modelling results.

5. MODELLING SOURCE CONTRIBUTIONS TO AMBIENT PARTICULATE MATTER (PM₁₀) IN KWADELA, MPUMALANGA

Introduction

Health impacts are determined by the PM concentrations produced in surface air and the amount inhaled by the relevant population, rather than total annual emissions (Zhou *et al.*, 2003). The extent to which PM penetrates the human respiratory system is mainly defined by the size of the particles (Balachandran *et al.*, 2000). As mentioned in previous chapters, PM is caused by various local pollution sources in these low-income settlements such as residential solid fuel burning, waste burning, and windblown dust as well as other sources such as industrial activities and background pollution. Human health is the major concern regarding air pollution and air pollution models are crucial for regulatory purposes and optimising appropriate site-specific abatement strategies that support local environmental policymaking. This should be addressed as large populations' health is affected by these air quality conditions on a daily basis; even more than that, these populations are not exposed to one pollutant at a time, but a mixture of various pollution chemicals (Mayer, 1999). The study that was done by Mayer (1999) on the 12 megacities of the world emphasised how the PM levels exceed the WHO guidelines by a factor of as much as two or three, contributing radically to the danger of health impacts.

Guidelines on how these environments' pollution concentrations should be modelled and regulated are still fairly unclear and complex, as mentioned in the previous chapter; further research is needed to elucidate the uncertainties (Moussiopoulos *et al.*, 2003). One of the uncertainties when modelling these scenarios is the relative contribution to air quality problems in these urban environments of different sources – local or otherwise. This raises an important question that needs clarification when guidelines are set on which sources are more important to monitor and model for regulatory purposes and which are of less importance. Therefore, in this chapter, AERMOD, the regulatory US EPA dispersion model, will be used to determine what the character of different source contributions is and whether local or other sources (such as industries) have a great impact on these urban environments' air quality.

5.1 Source contributions to urban air pollution

The first stage of urban air pollution is mainly caused by domestic sources and light industry; as population increases, industrial development and energy activities grow, thereby increasing pollution

levels. As urban air quality then becomes a health problem, pollution controls are set in place. Unfortunately, urban air pollution is complex with improvements being time-consuming and poor urban air quality endures until solutions are found and acted upon (Mayer, 1999).

Dispersion modelling can assist in the prediction of site-specific concentrations of pollutants from proposed sources and the ability to understand the mechanisms that determine the observed concentration characteristics (Held *et al.*, 1996).

Modelling urban air pollution has a few challenges, for instance, the receptor and the source having the same location, especially in the case of low-income settlements with domestic fuel burning as the source. The model has difficulty modelling these scenarios as the model is created to model pollution concentrations a distance away from the source. When modelling urban environments, it is important that the modelling system must be able to take local scale effects into account such as plume rise, building downwash, chemical transformation, and other pollution source obstacles.

One study that modelled source contributions in urban environments concluded that smoke from residential fuel burning – specifically coal – contributed more than 50% of PM in the monitored area (Engelbrecht *et al.*, 2000). Modelling results from another source contribution study stated that 45% of the PM₁₀ concentrations were caused by paved and unpaved road dust (Kleemann & Cass, 1998). In Beijing, road dust, coal burning, industrial emissions, vehicle exhaust emissions and waste incineration were identified as the major source contributors to PM₁₀ (Sun *et al.*, 2004).

There is a misconception about industrial emissions concerning health impacts: regulatory instruments focus mainly on these emissions, but these emissions are not found on an inhalable level as is the case with domestic fuel burning, windblown dust and waste burning, which are important factors that need to be taken into account. Industries do impact the air quality of the environment negatively and must take responsibility, but the importance thereof when health impacts are considered is overestimated in certain residential areas.

The fourth objective of this study is addressed in this chapter: to model different sources (local and other sources) contributing to ambient PM₁₀ and assess and characterise the relative air pollution contribution of windblown dust, domestic fuel burning, waste burning and surrounding coal-fired industries in Kwadela, Mpumalanga.

5.2 Results of modelled source contributions to ambient particulate matter (PM₁₀) in Kwadela, Mpumalanga

5.2.1 Windblown dust

Windblown dust contributes dominantly to PM levels modelled in Kwadela, as seen in Figure 5-2 displaying the diurnal contribution of windblown dust as a portion of all the sources modelled. Figure 5-1 displays the diurnal distribution of the contribution of windblown dust to the total modelled PM₁₀ for winter 2013. Figure 5-1 also includes the lower and upper concentrations modelled: the lower concentrations are calculated as the average minus the standard deviation and the upper concentrations as the average plus the standard deviation. Windblown dust modelled high concentrations especially early in the morning and late in the evening. There is a large variability in the concentrations of up to 80µg/m³. It should be noted that windblown dust is dependent on variables such as weather conditions, including wind, rainfall, and soil type, which make it an inconsistent pollution source. However, when the conditions are favourable for dispersion, this source can make a considerable contribution to PM concentrations.

Comparing these contributions to the total PM levels modelled, windblown dust is to be considered when regulatory instruments are set in place. It is important to note that emission factors were used to calculate emissions and that the differences in values might highlight variations in complexity, conservatism and local applicability between emission factors. Considering air quality in these low-income settlements in SA, empty open spaces with little to none vegetation, especially in the direct environment of the houses and unpaved roads, occur often, both contributing to the potential windblown dust as a pollution source.

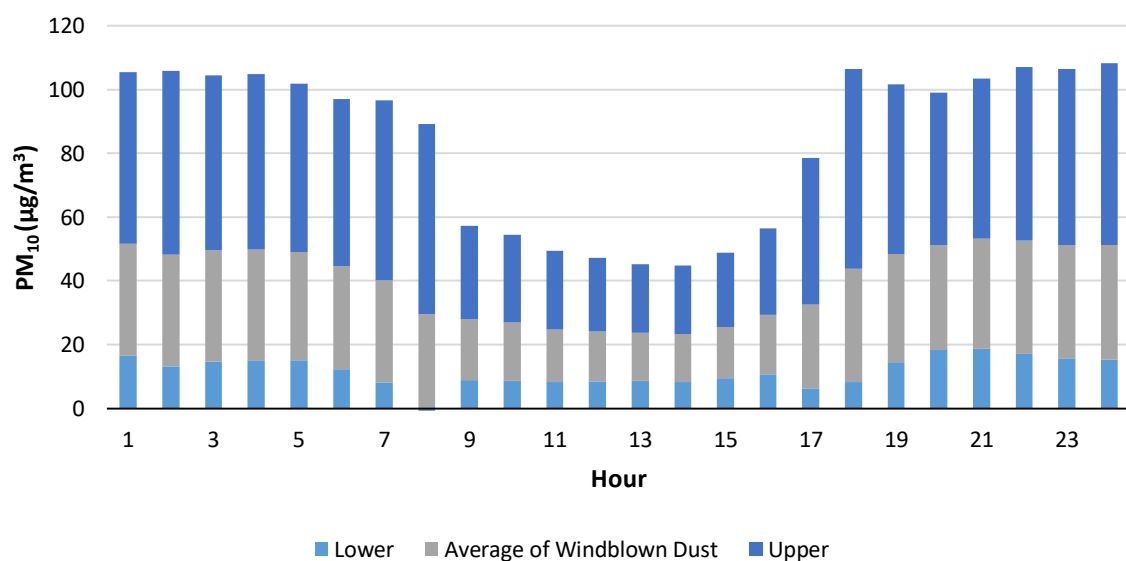


Figure 5-1. Distribution of lower (average minus standard deviation), average and upper (average plus standard deviation) hourly contributions to modelled concentrations of windblown dust

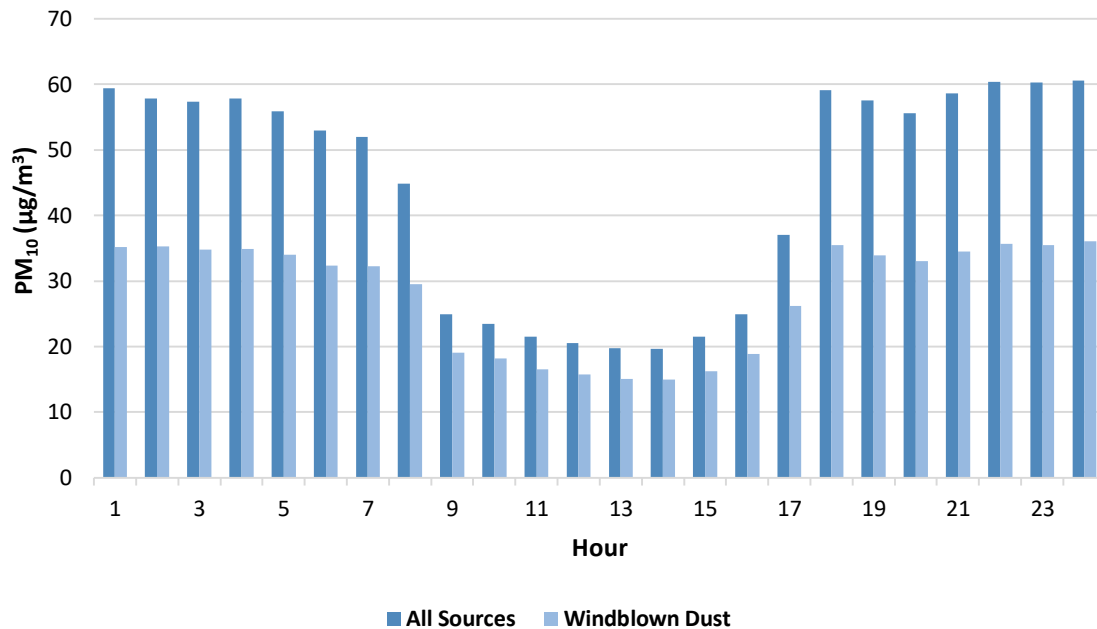


Figure 5-2. Distribution of the hourly average contribution of windblown dust to the total modelled PM₁₀ for winter 2013

5.2.2 Domestic fuel burning

Domestic fuel burning is the pollution source contributing second most to the PM levels (Figure 5-9) and was modelled as a constant polluting source (details outlined in section 3.4.4.1). Figure 5-3 also includes the lower and upper concentrations modelled: the lower concentrations are calculated as the average minus the standard deviation and the upper concentrations as the average plus the standard deviation. Different from windblown dust being dependent on variables such as suitable weather conditions, domestic fuel burning is a consistent polluting source caused by human activity, with particularly high levels of PM in the mornings (9:00-12:00) and in the evenings (18:00-21:00) being the peak times for cooking and heating. In Figure 5-3, it can be seen that the highest contributions were modelled during the early mornings (01:00-06:00) and later evenings (18:00-00:00), with a high peak being measured 75µg/m³. The pollution from this source is distributed among the entire residential area, impacting the health of the entire population. Unfortunately, women and the more vulnerable part of the population are constantly exposed to these high PM levels as the children and elderly stay at home most of the time. The rest of the population is also impacted as the peak PM levels are measured during times of the day when many of the working family members have returned to the settlement.

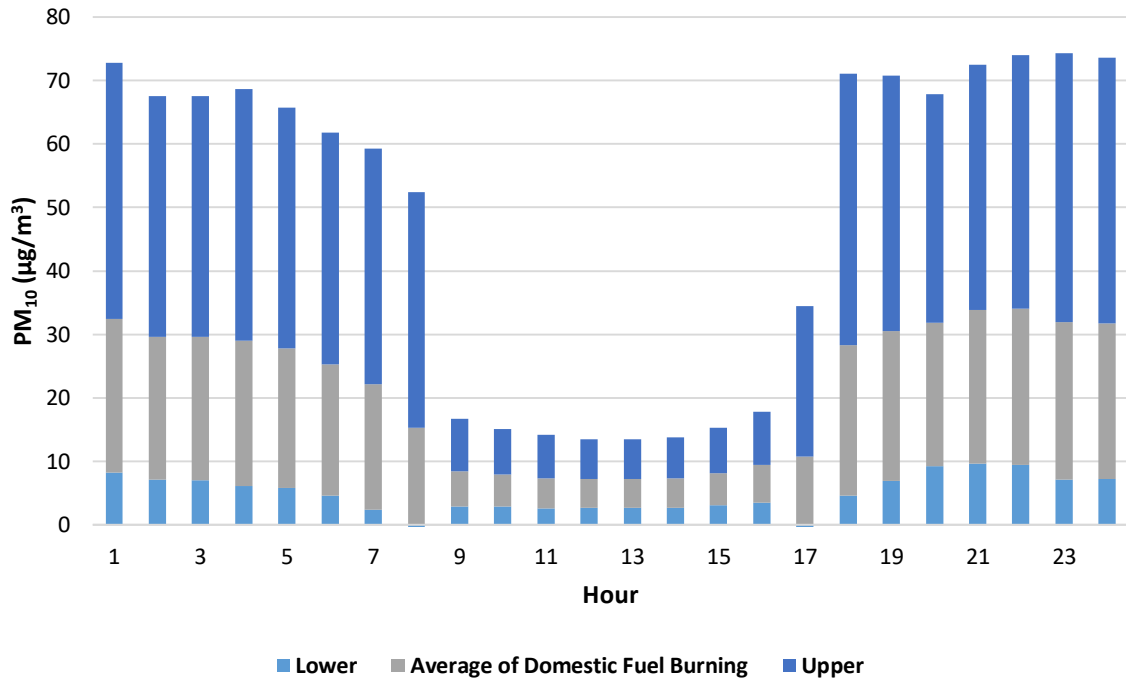


Figure 5-3. Distribution of lower (average minus standard deviation), average and upper (average plus standard deviation) hourly contributions to modelled concentrations of domestic fuel burning during winter, 2013

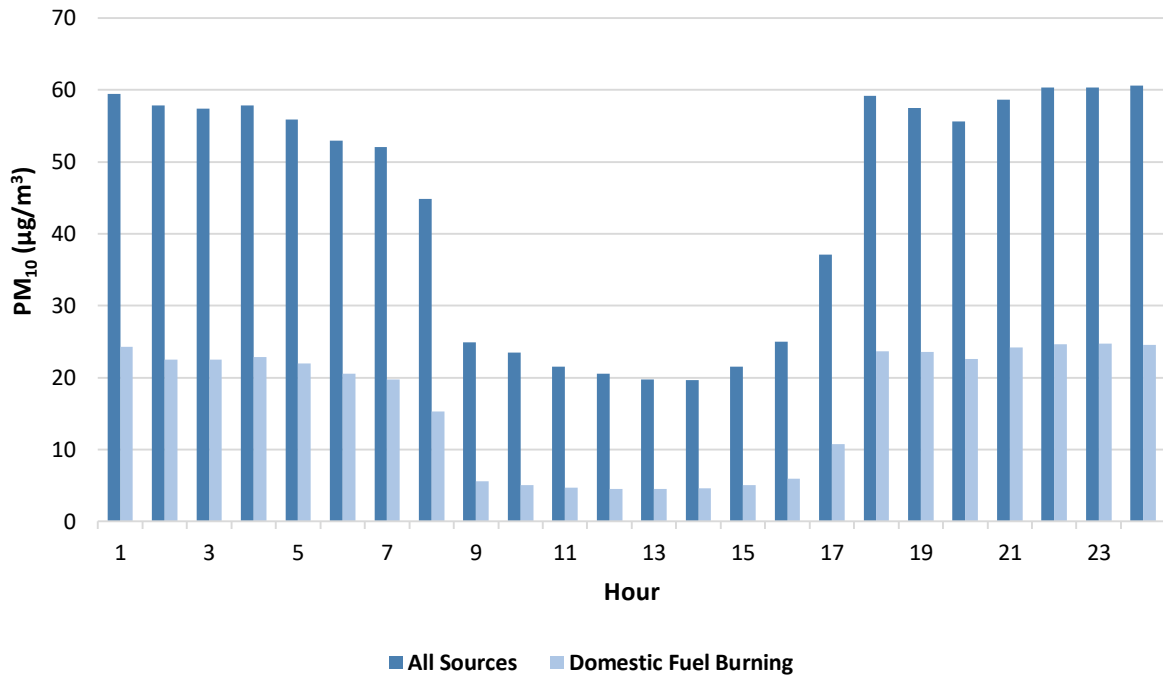


Figure 5-4. Distribution of the hourly average contribution of domestic fuel burning to the total modelled PM₁₀ for winter 2013

5.2.3 Industries

The industrial coal-fired power stations contributed very little to the total PM levels as seen in Figure 5-6. Some argue that surrounding industrial sources make the biggest contribution to pollution levels, but these results indicate the opposite. Although these industrial sources are located some kilometres away from Kwadela, their impacts are definitely not enough to be described as the/one of the dominant pollution sources contributing to PM causing health impacts. Although the modelled PM levels contributed by industries are low, the highest concentrations were modelled during 09:00 and 17:00 (Figure 5-5). It should also be noted that pollution from these industrial stacks has a much higher release height than that of waste burning, windblown dust and domestic fuel burning and as the receptors and pollution sources are not in the exact same location such as that of the other three considered sources, it travels a distance and is already dispersed in the atmosphere before reaching an inhalable location. These results confirm that local sources do contribute greatly and dominantly to the PM levels of Kwadela, especially windblown dust and domestic fuel burning as opposed to other surrounding pollution sources such as nearby industries.

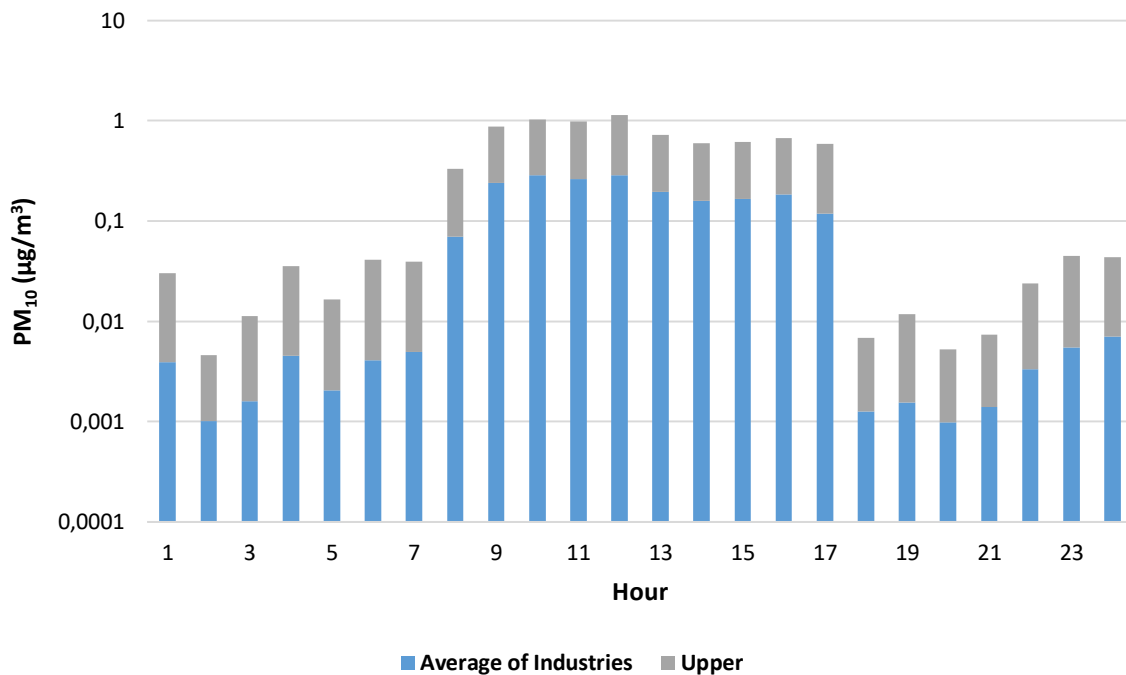


Figure 5-5. Distribution of average and upper (average plus standard deviation) hourly contributions to modelled concentrations of surrounding industrial sources during winter, 2013

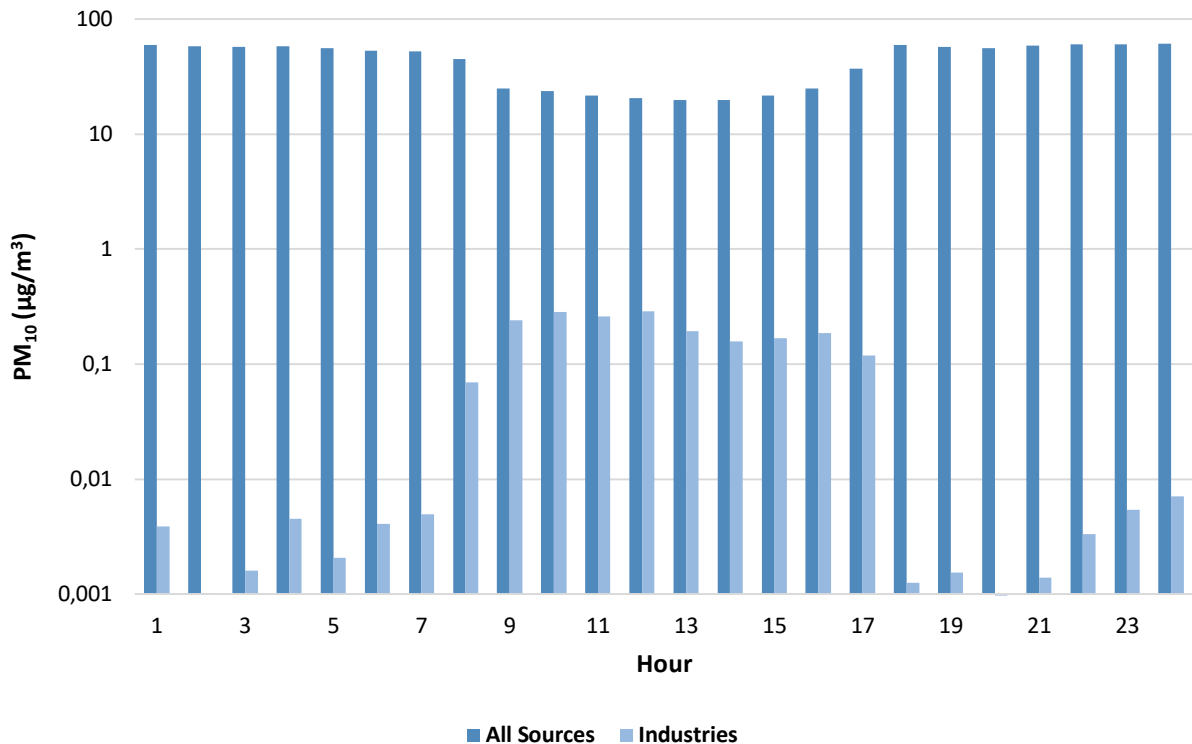


Figure 5-6. Distribution of the hourly average contribution of surrounding industrial sources to the total modelled PM₁₀ for winter 2013

5.2.4 Waste burning

The daily diurnal patterns of pollution caused by waste burning show higher concentrations during early morning (01:00-05:00) and late evening (21:00 and onward) with a clear decline in modelled observations occurring during mid-day (Figure 5-7). Waste burning contributed the least of all the sources according to the modelled concentrations (Figure 5-8). This result is influenced because reality and the census (2011) results used to calculate the final emission rate for waste-burning do not correlate. In Kwadela, there are a few visible waste burning dumps definitely contributing to PM levels, but the census data indicated that only 15% of all waste is not taken away by public services, implying that only 556 out of 3 708 people contribute to waste burning, which is not the case observed during the site visits. The failure of public services to fulfil their obligation compromises the census data and, by extension, the accuracy of the modelled results. Comparing the reality with the modelling results, it can be concluded that waste burning emissions are estimated to be lower than reality, although the error does not lie with the model, but rather the accuracy of the data needed to calculate the emission rate used as input in the model, also confirming the importance of correct inputs.

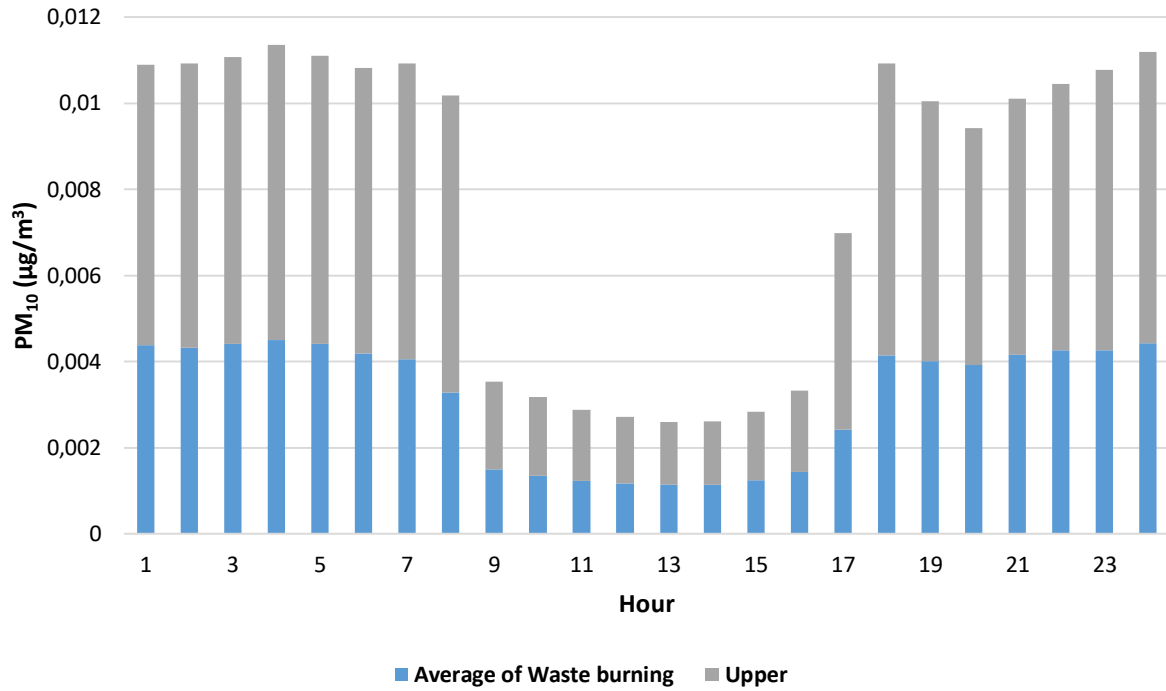


Figure 5-7. Distribution of average and upper (average plus standard deviation) hourly contributions to modelled concentrations of waste burning during winter, 2013

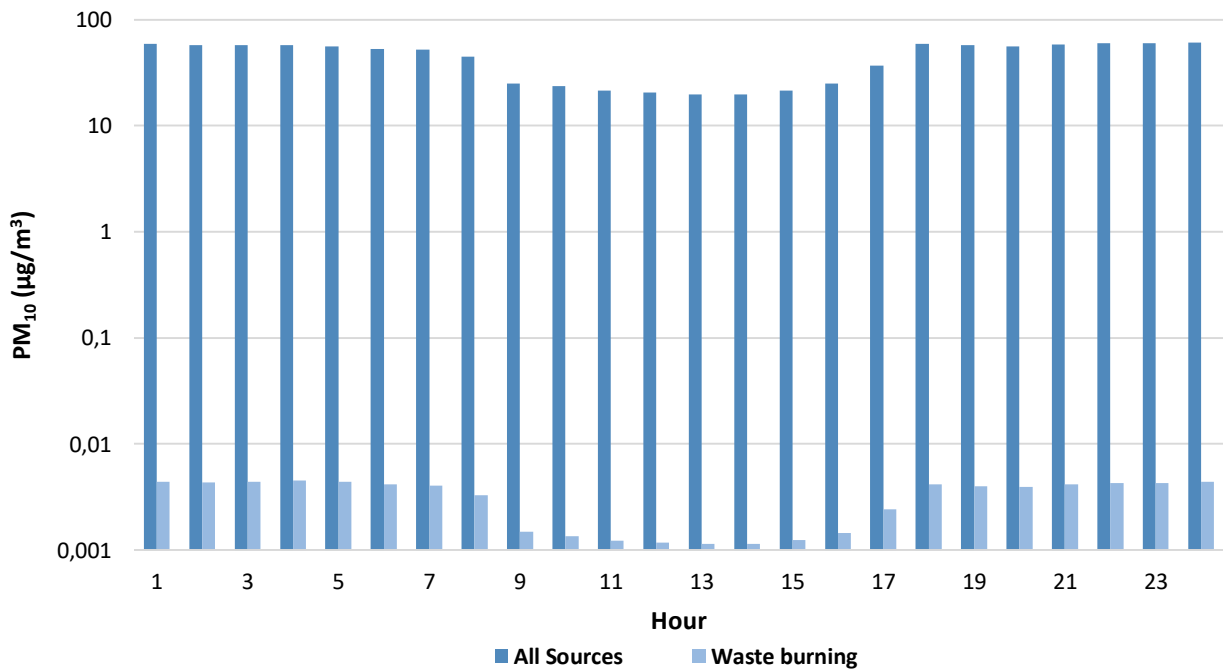


Figure 5-8. Distribution of the hourly average contribution of waste burning to the total modelled PM₁₀ for winter 2013

5.3 Relative source contributions to ambient particulate matter (PM₁₀) in Kwadela

According to the modelling results of section 5.2, windblown dust and domestic fuel burning make the largest contribution to the ambient air pollution as seen in the modelled results in Table 5-1, Figure 5-9 and Figure 5-10, while waste burning and surrounding coal-fired industrial sources contributed significantly less.

Table 5-1: Hourly concentrations modelled (PM₁₀)

	All sources	Domestic fuel burning	Waste burning	Windblown dust	Industries
Average concentration (µg/m ³)	44	16	0.003	28	0.1
Maximum concentration (µg/m ³)	270	114	0.09	162	3
Minimum concentration (µg/m ³)	7	1	0.0005	5	0.00002

Source Contributions

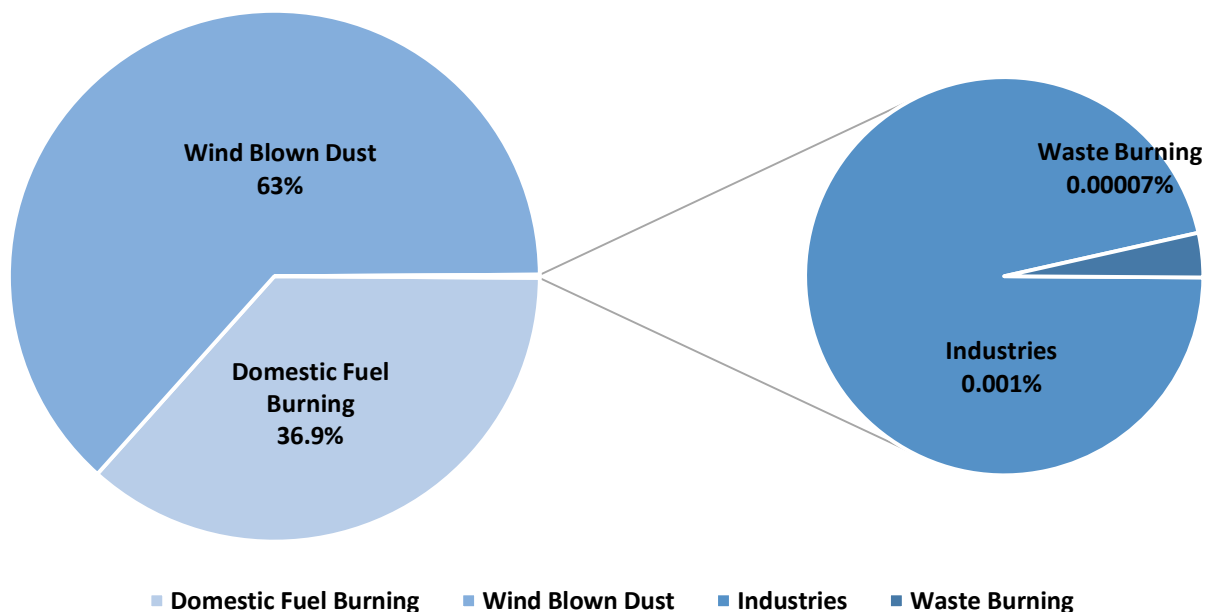


Figure 5-9. A pie chart of the relative contributions of different air pollution sources in Kwadela

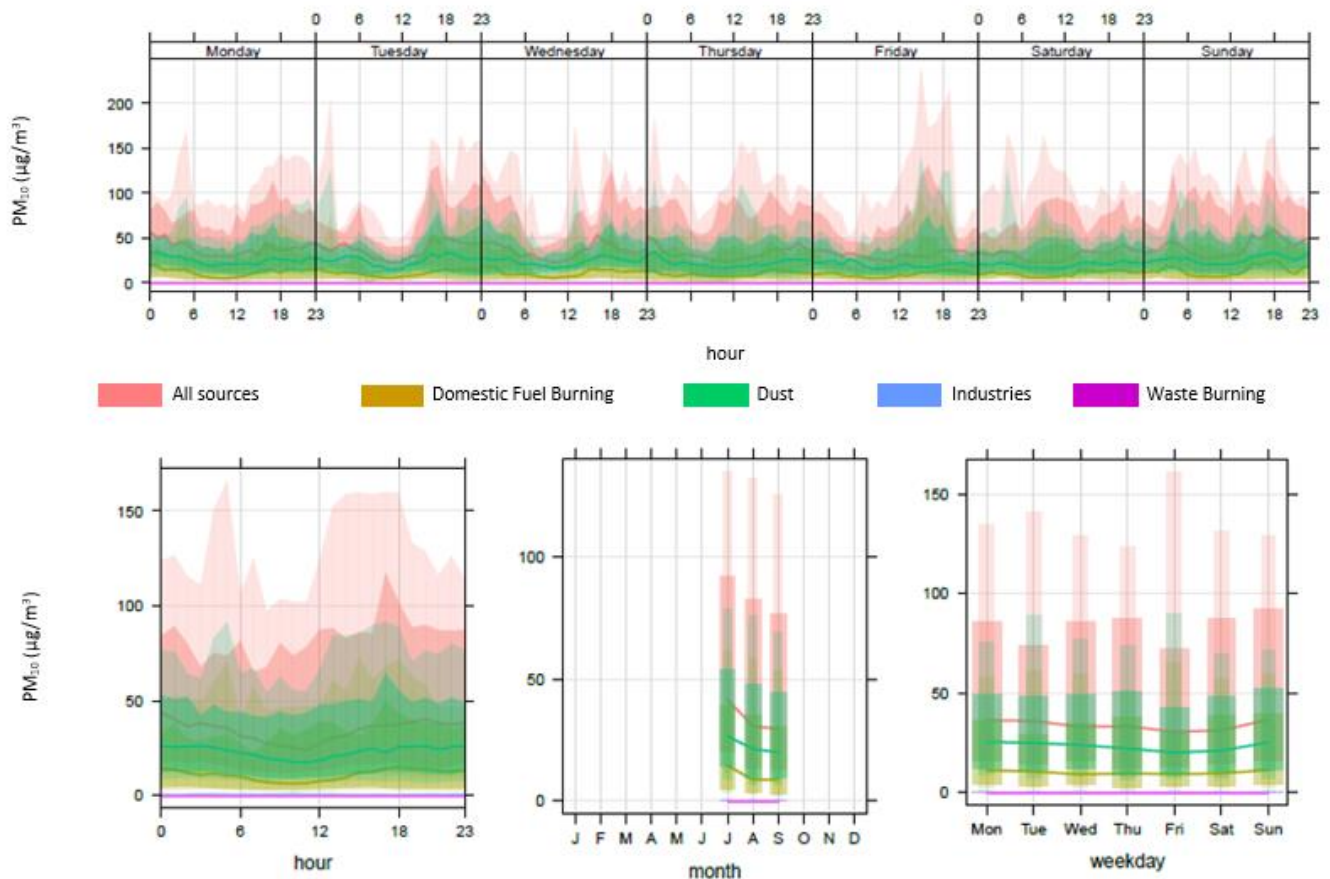


Figure 5-10. The relative contribution of different sources in Kwadela

5.4 Modelled results compared to the Kwadela Ambient Air Quality Monitoring Campaign's results

In this modelling scenario (inputs outlined in section 3.4 and results from section 5.3), one of the shortcomings is that secondary and background air quality was not taken into account, only primary pollutants. In reality, secondary pollutants play an important role, especially when distance and time are involved, influencing the formation of secondary pollutants.

As Taylor diagrams display how closely a modelled pattern or a set of patterns match observed results, they were not used in this analysis as the focus was only on one point, the caravan monitoring site in Kwadela, being modelled and monitored, and not a comparison of multiple aspects of a few models.

The monitored and modelled PM₁₀ results are compared to one another in Figure 5-11 with the use of a Q-Q plot. The model predicts the lower values fairly reliably compared to the monitored concentrations, but with higher concentrations, the model underestimates as it continuously displays lower than the monitored values in Figure 5-11. This is not ideal as the preferred performance of the model would be to overestimate rather underestimate, and consequently the modelled predictions

will be conservative and ensure compliance with ambient air quality regulatory frameworks and policy standards.

The diurnal and daily modelled and monitored concentrations are compared in Figure 5-12 and Figure 5-13. Analysing the diurnal pattern of Figure 5-12, there is a positive correlation between the modelled and monitored concentrations early in the morning and then again later in the afternoon; however, there is a negative correlation during the other hours. As mentioned when discussing the Q-Q plot, the scatter plots both indicate that the model underpredicted. If background data is taken into account, this could change the predicted concentrations to be more conservative and over-predict rather than under-predict. For Figure 5-13, there seems to be less correlation between monitored and modelled concentrations, where again, if background data is taken into account, this would change the distribution to display higher modelled concentrations. There are some outliers on the scatter plot indicating some monitored peak concentrations and some very low concentrations were modelled. The overall performance of the model on an hourly and daily scale is not as successful, but on a larger time scale, the model would perform better and make a valuable contribution to air quality predictions to use for policy and regulatory purposes.

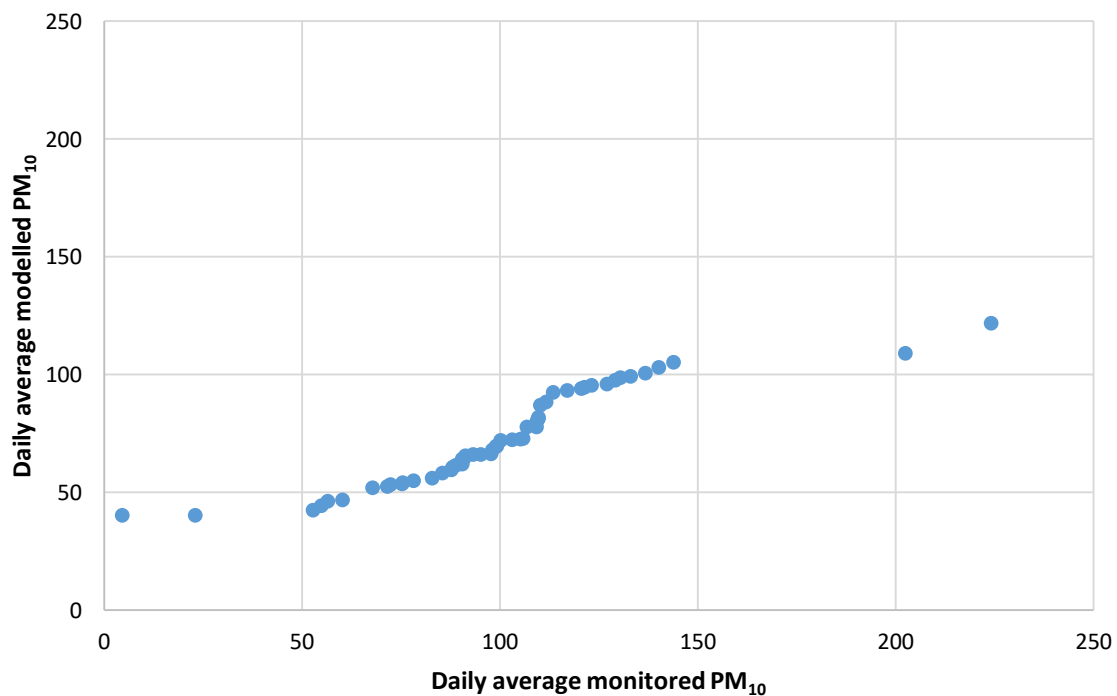


Figure 5-11. Q-Q plot of modelled versus monitored daily average PM₁₀ concentrations

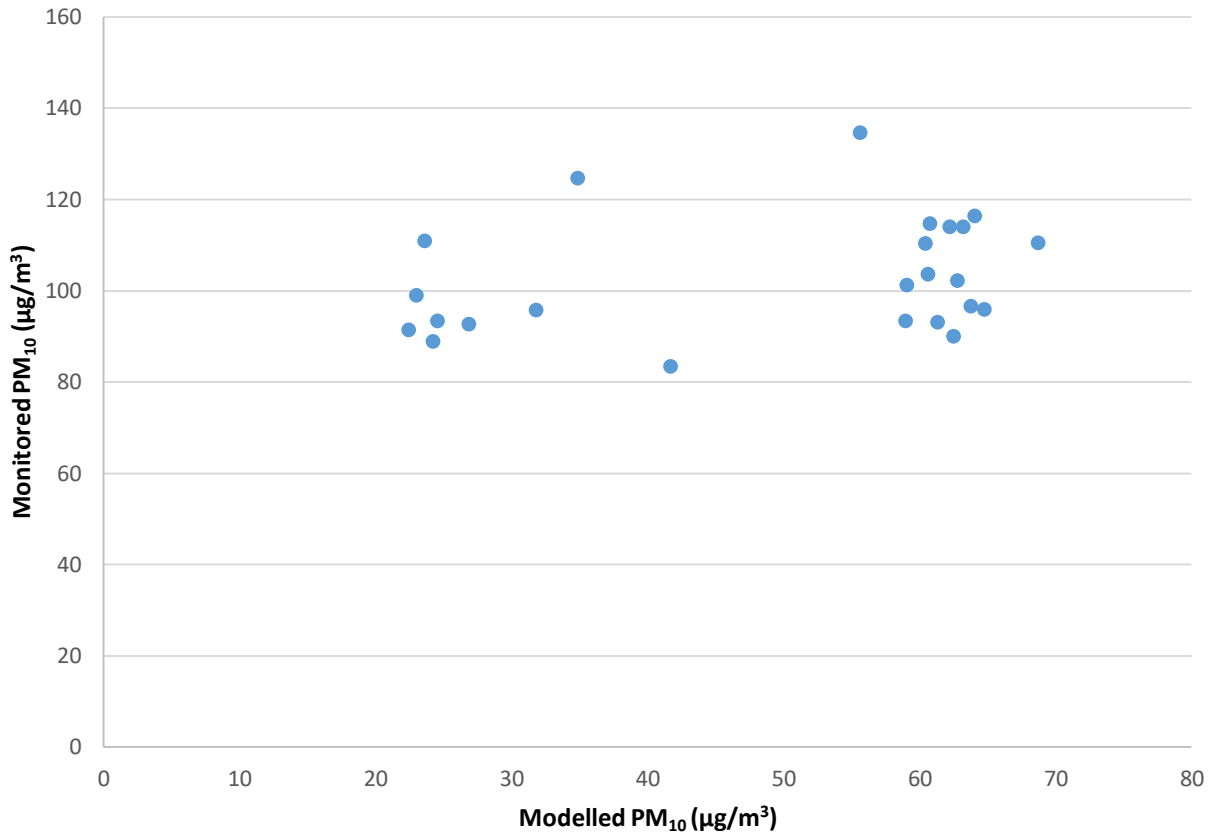


Figure 5-12. Scatter plot of modelled versus monitored hourly average PM₁₀ concentrations during winter, 2013

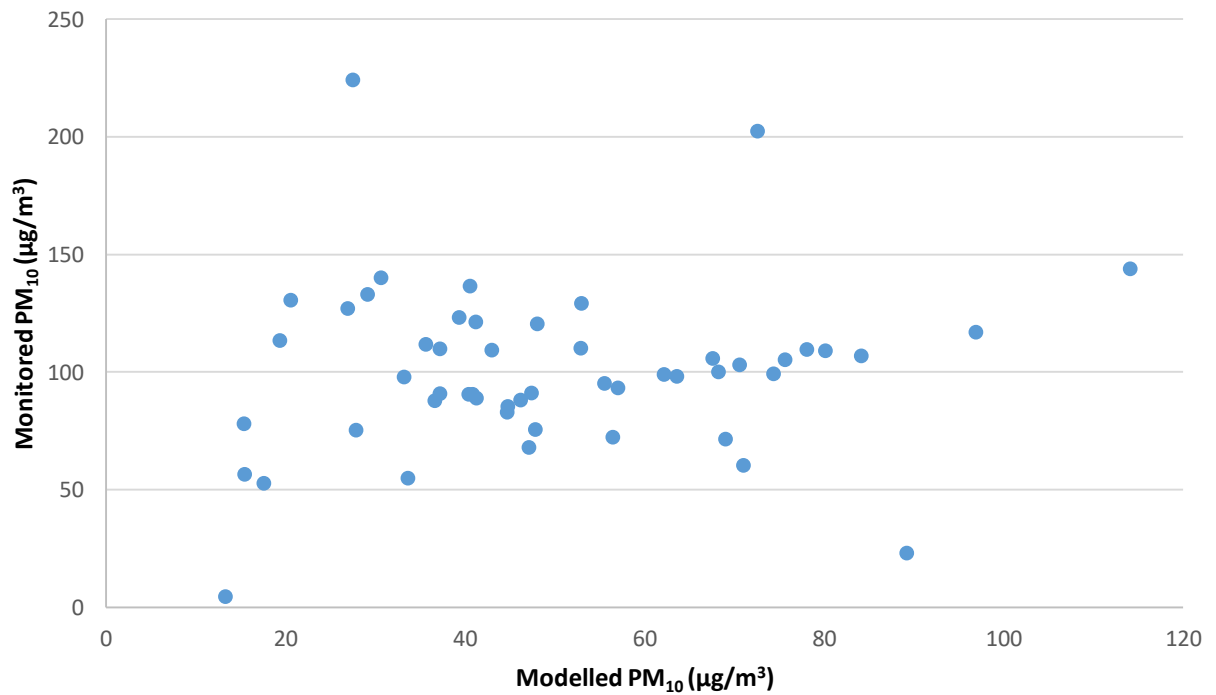


Figure 5-13. Scatter plot of modelled versus monitored daily average PM₁₀ concentrations during winter, 2013

5.5 Chapter conclusion

Modelling the air pollution of urban environments caused by distributed sources is complicated as the results from each modelling scenario can differ with just a few changes. Numerous options are available and choices such as emission factors, modelling options, meteorological data and source parameters greatly influence the results. Modelling the contribution of different sources, especially complex sources such as domestic fuel burning and windblown dust, can have various errors and difficulties that should be considered. A case study was done where four pollution sources were modelled, three local sources namely domestic fuel burning, windblown dust and waste burning, and one other source namely industries within a 50km radius of Kwadela. The objectives of this chapter were first to model these sources contributing to ambient PM_{10} and secondly to assess and characterise the relative air pollution contribution of each source in Kwadela. Windblown dust and domestic fuel burning modelled the highest PM-concentrations, impacting the everyday health of Kwadela's population, especially since the release height is at an inhalable height and is permanently in the midst of their daily activities. Waste burning and industrial sources contributed the least of all the sources. This supports the argument that local sources have an immense impact and make the largest contribution to PM levels within residential areas, especially in low-income communities of Southern Africa where windblown dust and domestic fuel burning are unavoidable in the everyday lives of the residents. These two pollution sources should be taken into account when air quality policies are made.

The overall model performance was also evaluated by comparing the modelled and monitored concentrations, and to conclude the overall performance of the model on an hourly and daily scale is not as successful, but on a larger time scale, the model would perform better and make a valuable contribution to air quality predictions to use for policy and regulatory purposes.

6. CONCLUSIONS

The overall aim of this study is to assess the performance of a steady-state Gaussian dispersion model when simulating ambient air quality for regulatory purposes in a low-income urban area on the South African Highveld. The evaluation was done from the basis of the following research objectives: (1) characterise the ambient PM loading and variability of five low-income urban areas on the South African Highveld; (2) evaluate the sensitivity of simulated ambient particulate matter to model inputs in Kwadela, Mpumalanga, by comparing different dispersion modelling scenarios; and (3) model and assess the relative contribution of domestic fuel burning, windblown dust, waste burning and surrounding coal-fired industrial sources to ambient PM concentrations in the small low-income settlement of Kwadela, Mpumalanga.

6.1 Contributions to the broader body of knowledge

This study contributes firstly by characterising the ambient PM loading and variability of five low-income urban areas on the South African Highveld, secondly, the sensitivity of simulated ambient particulate matter to model inputs is outlined. Thirdly, when intra-urban air quality is modelled for regulatory purposes, the importance of the relative contribution of various sources to air pollution levels being evaluated assists in knowing which sources should be focused on and taken into consideration when air pollution regulations are discussed.

6.2 Characterising the ambient particulate matter loading and variability of five low-income urban areas on the South African Highveld

- The ambient air quality of urban settlements varies in space and time, but they exceed the NAAQS daily and should raise concerns. Peak concentrations are found in the mornings between 5am and 10am and in the afternoon between 5pm and 10pm, linking to the time for cooking and heating and when the largest part of the settlement's population is at home.
- Isolated high measurements are also present during midday.
- Kwadela's exceedances are noticeably high, being higher than the ambient standards 50% of the time during winter.
- The diurnal and daily distribution of PM₁₀ levels displays the consistent presence of poor ambient air quality in these urban settlements exceeding the daily NAAQS.
- The high PM levels show that even small settlements have ambient concentrations well in excess of the NAAQS.

6.3 Evaluation of the sensitivity of simulated ambient particulate matter to model inputs in Kwadela, Mpumalanga, by comparing different dispersion modelling scenarios

- Modelling pollution sources in urban environments is complex as there are simply a large number of input options influencing the output, contributing to the variability as well as the possibility of errors to occur for each modelling scenario. Minor changes in these variables change the distance within which concentration restrictions are surpassed by several hundred meters, and therefore the sensitivity of these models should also be taken into account. This emphasises the importance of well-estimated input data to be used when modelling intra-urban air pollution.
- Every intra-urban scenario is unique and this makes modelling these ambient air quality conditions complex as variability is difficult to account for.
- Emission inventories for PM are critical in establishing how sources affect health and need to be continuously improved. To date, emission factors from the literature are still adopted in the development of emission inventories. However, there is currently a lack of sufficient and reliable data, especially for emission factors, which leads to uncertainties and bias in many emission inventories due to influences of a variety of parameters.
- AERMOD dispersion model has difficulty modelling the conditions at hand as, for example, the model was designed to model air pollution concentrations a distance away from the source and not close to or at exactly the same location as is the case of intra-urban air pollution.
- The variability in results illustrates the urgent need for strict guidelines on how these scenarios should be approached and modelled.
- Changing the ER and the type of source, e.g. point sources or area source, made the largest impact on the results. In model runs 1 and 3, domestic fuel burning was represented as an area source, being Kwadela as a whole and the concentrations measured were significantly lower than model runs 2 and 4, where domestic fuel burning was represented as point sources, each a household in the settlement.
- Variability in emission rates and the source type chosen to represent the source had the largest influence on the modelling results.

6.4 The relative contribution of different sources to air pollution in Kwadela

Thereafter, a case study was done where four pollution sources were modelled, three local sources namely windblown dust, domestic fuel burning and waste burning, and one other source namely industries within a 50km radius from Kwadela.

- Waste burning and industrial sources contributed the least of all the sources.
- Windblown dust modelled the highest PM concentrations and made the largest contribution to PM levels, domestic fuel burning modelled second highest, impacting the everyday health of Kwadela's population.
- Since the release height of these two sources is at an inhalable height and they are permanently in the midst of everyday activities of the population, they are crucial for regulatory purposes.
- This supports the argument that local sources have an immense impact and make the largest contribution to PM levels within residential areas, especially in low-income communities where windblown dust and domestic fuel burning are inevitably part of the community's existence.
- A more efficient way to model windblown dust and domestic burning has the potential to assist in testing or designing mitigation options.

As the air quality investigation was done in South Africa, a developing country with numerous urban settlements, it is a prime example of the occurrence of the poor air quality conditions.

The worldwide occurrence, poor management, and significance of the related health impacts make urban air pollution a source of great concern. PM with a diameter of 10 μ m and less has harmful impacts on human health, and therefore proper policy and legislation must be put in place to manage ambient air quality in urban environments. It is unfortunate that these dispersion models, used for regulatory purposes, have difficulty determining the air pollution levels in an environment that directly impacts the daily health of the population in developing countries such as South Africa. Typical regulatory instruments target industrial and other processes that can be understood and manipulated relatively easily. The emissions of intra-urban air quality, especially low-income settlements, contribute significantly to health impacts, but are difficult to understand, calculate, model and most of all, manage in reality and this should raise great concern and consideration in statutory policy-making.

Gaussian dispersion models are therefore not flawless when analysing intra-urban air pollution; however, realising how complicated the challenges are, the significance of the quality of the data being used and the need to model intra-urban centres' air quality validate the AERMOD dispersion model as an appropriate tool to use for these simulations.

REFERENCES

- Albalak, R., Frisanchio, A.R. & Keeler, G.J. 1999. Domestic biomass fuel combustion and chronic bronchitis in two rural Bolivian villages. *Thorax*, 54(11):1004-1008.
- Albalak, R., Haber, M., Frisanchio, A.R. & Keeler, G.J. 1999. Assessment of PM₁₀ concentrations from domestic biomass fuel combustion in two rural Bolivian Highland Villages. *Environmental Science & Technology*, 33(15):2505-2509.
- Annegarn, H.J. 2006. Implications of the new Air Quality Act for the Residential Built Environment. *Environmental Management Journal*, 37:18-21.
- Annegarn, H.J., Terblanche, A.P.S., Sithole, J.S., Rorich, R.P. & Turner, C.R. Residential Air Pollution in Held, G., Gore B.J., Surridge, A.D., Tosen G.R., Turner, C.R. & Waernshey, R.D. 1996. Air Pollution and its Impacts on the South African Highveld. Environmental Scientific Association, Cleveland, 144pp.
- Annegarn, H.J. & Sithole, J.S. 1999. Soweto Air Monitoring Project (SAM), Quarterly report to the Department of Minerals and Energy, report no. AER 20.001 Q-SA. University of the Witwatersrand, Johannesburg.
- Arku, R.E., Vallarino, J., Dionisio, K.L., Willis, R., Choi, H., Wilson, J.G., Hemphill, C., Agyei-Mensah, S., Spengler, J.D. & Ezzati, M. 2008. Characterizing air pollution in two low-income neighbourhoods in Accra, Ghana. *Science of the Total Environment*, 402:217-231.
- Aurela, M., Beukes, J.P., Van Zyl, P.G., Vakkari, V., Teinilä, K., Saarikoski, S. & Laakso, L. 2016. The composition of ambient and fresh biomass burning aerosols at a savannah site, South Africa. *South African Journal of Science*, 112(5-6):1-8.
- Bailis, R., Ezzati M., Kammen D.M. 2005. Mortality and greenhouse gas impacts of biomass and petroleum energy futures in Africa. *Science*, 308(5):98-103.
- Balachandran, S., Bharat, R.M. & Khillare, P.S. 2000. Particle size distribution and its elemental composition in the ambient air of Delhi. *Environment International*, 26(1-2):49-54.
- Balmer, M. 2007. Household coal use in an urban township in South Africa. *Journal of Energy in Southern Africa*, 18(3):27-32.

- Barnes, B., Mathee, A., Bruce, N. & Thomas, L. 2009. Household energy, indoor air pollution and child respiratory health in South Africa. *Journal of Energy in South Africa*, 20(1):4-13.
- Bell, M.L., Dominici, F., Ebisu, K., Zeger, S.L. & Samet, J.M. 2007. Spatial and temporal variation in PM_{2.5} chemical composition United States for health effects studies. *Environmental Health Perspectives*, 115(7):989-995.
- Bellander T., Berglind N., Gustavsson P., Jonson T., Nyberg F. & Pershagen G. & Järup. 2001. Using geographic information systems to assess individual historical exposure to air pollution from traffic and house heating in Stockholm. *Environmental Health Perspectives*, 109(6):633-639.
- Berkowicz, R., Olesen, H.R. & Torp, U. 1992. Air pollution modelling and its application 9th ed. Plenum Press, New York, p.29-38.
- Bizzo, W.A., De Calan, B., Meyers, R. & Hannecart, T. 2004. Safety issues for clean liquid and gaseous fuels for cooking in the scope of sustainable development. *Journal of Energy for Sustainable Development*, 8(3):60-67.
- Boman, B.C., Forsberg, A.B. & Järholm, B.G. 2003. Adverse health effects from ambient air pollution in relation to residential wood combustion in modern society. *Scandinavian Journal of Work, Environment & Health*, 29(4):251-260.
- Briggs, D. 2000. Exposure assessment. (In Elliott P., Wakefield J., Best N., & Briggs D., ed. *Spatial Epidemiology: Methods and Applications*. Oxford: Oxford University Press, p.335-359).
- Brook, R.D., Rajagopalan, S., Pope III, C.A., Brook, J.R., Bhatnagar, A., Diez-Roux, A.V., Holguin, F., Hong, Y., Luepker, R.V., Mittleman, M.A., Peters, A., Siscovick, D., Smith, S.C., Whitsel, L. & Kaufman, J.D. 2010. Particulate matter air pollution and cardiovascular disease - An update to the scientific statement from the American Heart Association. *AHA Scientific Statement*, 121:2331-2378.
- Bruce, N., Perez-Padilla, R. & Albalak, R. 2000. Indoor air pollution in developing countries: a major environmental and public health challenge. *Bulletin of the World Health Organization*, 78(9):1078-1092.
- Brunekreef, B. & Holgate, S.T. 2002. Air pollution and health. *The Lancet*, 360(9341):1233-1242.

- Burger, R.P. 2016. The distribution of aerosol and trace gases in lower troposphere over South Africa. Johannesburg: University of Johannesburg (Thesis – PhD).
- Butt, E.W., Rap, A., Schmidt, A., Scott, C.E., Pringle, K.J., Reddington, C.L., Richards, N.A.D., Woodhouse, M.T., Ramirez-Villegas, J., Yang, H., Vakkari, V., Stone, E.A., Rupakheti, M., Praveen, P.S., van Zyl, P.G., Beukes, J.P., Josipovic, M., Mitchell, E.J.S., Sallu, S.M. & Forster, P.M. 2015. The impact of residential combustion emissions on atmospheric aerosol, human health and climate. *Atmospheric Chemistry & Physics Discussions*, 15(14):20449-20520.
- Cairncross, E.K. & John, J. 2004. Communicating air pollution exposure: a novel air pollution index system based on the relative risk of mortality associated with exposure to the common urban air pollutants. IUAPPA 13th Annual World Clean Air and Environmental Protection Congress and Exhibition. London: IUAPPA.
- Cairncross, E.K., John, J. & Zunckel, M. 2007. A novel air pollution index based on the relative risk of daily mortality associated with short-term exposure to common air pollutants. *Atmospheric Environment*, 41(38): 8442-8454.
- Cairncross, E.K. & Mtiya, K. 2013. The comparability of modelled concentrations using alternative meteorological datasets: A case study of SO₂ dispersion from a large stationary source. *Clean Air Journal*, 23(1):11-14.
- Cambridge Environmental Research Consultants. 2010. Compilation of emissions inventory and preliminary air quality modelling for Cape Town. Technical report.
- Capaldo, K., Corbett, J.J., Kasibhatla, P., Fischbeck, P. & Pandis, S.N. 1999. Effects of ship emissions of sulphur cycling and radiative climate forcing over the ocean. *Nature*, 400(6746):743-746.
- Carruthers, D.J., Holroyd, R.J., Hunt, J.C.R., Weng, W.S., Robins, A.G., Apsley, D.D., Thompson, D.J. & Smith, F.B. 1994. UK-ADMS: A new approach to modelling dispersion in the earth's atmospheric boundary layer. *Journal of Wind Engineering and Industrial Aerodynamics*, 52:139-153.
- Chowdhury, M.Z. 2004. Characterization of fine particle air pollution in the Indian subcontinent. Atmospheric Chemistry. Georgia Institute of Technology (Thesis – PhD).

- Christopher, A.J. 2014. Headlining the release of South Africa's Census 2011 results. *South African Geographical Journal*, 96(2):166-179.
- Cimorelli, A.J., Perry, S.G., Venkatram, A., Weil, J.C., Paine, R.J., Wilson, R.B., Lee, R.F., Peters, W.D. & Brode, R.W. 2005. AERMOD: A dispersion model for industrial source applications. Part I: general formulation and boundary layer characterization. *Journal of Applied Meteorology*, 44:682-693.
- Cohen, A.J., Anderson, H.R., Ostro, B., Dev Pandey, K., Krzyzanowski, M., Künzli, N. Gutschmidt, K., Pope, C.A., Romieu, I., Samet, J.M. & Smith, K.R. 2005. The Global Burden of Disease due to Outdoor Air Pollution. *Journal of Toxicology and Environmental Health*, 68(14-15): 1301-1307.
- Cooper, J.A. 2012. Environmental impact of residential wood combustion emissions and its implications. *Journal of Air Pollution Control Association*, 30(8):855-861.
- Croner, C.M., Sperling, J. & Broome, F.R. 1996. Geographic information systems (GIS): new perspectives in understanding human health and environmental relationships. *Statistics in Medicine*, 15(18):1961-1977.
- Cyrys, J., Hochadel, M., Gehring, U., Hoek, G., Diegmann, V., Brunekreef, B. & Heinrich, J. 2005. GIS-Based estimation of exposure to particulate matter and NO₂ in an urban area: stochastic versus dispersion modelling. *Environmental Health Perspectives*, 113(8):987-992.
- Dab, W., Quénel, S.M.P., Moulec, Y.L., Tertre, A.L., Thelot, B., Monteil, C., Lameloise, P., Pirard, P., Momas, I., Ferry, R. & Festy, B. 1996. Short term respiratory health effects of ambient air pollution: results of the APHEA project in Paris. *Journal of Epidemiology and Community Health*, 50(1):42-46.
- Damm, O. & Triebel, R. 2008. A synthesis report on biomass energy consumption and availability in South Africa. A report prepared for ProBEC, GTZ.
- De Koning, H.W., Smith, K.R. & Last, J.M. 1985. Biomass fuel combustion and health. *Bulletin of the World Health Organization*, 63(1):11-26.
- DoE (Department of Energy). 2012. Annual Report 2011/2012. Department of Energy, Pretoria.

- Dennis, R.L., Buyn, D.W. & Novak, J.H. 1996. The next generation of integrated air quality modelling: EPS's models-3. *Atmospheric Environment*, 30(12):1925-1938.
- Dockery, D.W., Pope, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G. & Speizer, F.E. 1993. An association between air pollution and mortality in six US cities. *New England Journal of Medicine*, 329:1753-1759.
- Echalar, F., Gaudichet, A., Casier, H. & Artaxo, P. 1995. Aerosol emissions by tropical forest and savannah biomass burning: Characteristic trace elements and fluxes. *Geophysical Research Letters*: 22(22):3039-3042.
- El-Fadel, M. & Massoud, M. 2000. Particulate matter in urban areas: health-based economic assessment. *Science of the Total Environment*: 257(2-3):133-146.
- Engelbrecht, J.P., Reddy, V.S., Swanepoel, L. & Mostert, J.C. 1998. Aerosol monitoring and source apportionment in the Vaal Triangle. Special Publication no. 17. Mintek, Randburg, South Africa. pp. 135.
- Engelbrecht, J.P., Swanepoel, L., Zunckel, M., Chow, J.C., Watson, J.G. & Egami, R.T. 2000. Modelling PM₁₀ aerosol data from the Qalabotjha low-smoke fuels macro-scale experiment in South Africa. *Ecological Modelling*, 127:235-244.
- Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G. & Egami, R.T. 2001. PM_{2.5} and PM₁₀ concentrations from the Qalabotjha low-smoke fuels macro-scale experiment in South Africa. *Environmental Monitoring and Assessment*, 69(1):1-15.
- Engelbrecht, J.P., Swanepoel, L., Chow, J.C. & Watson, J.G. 2002. The comparison of source contributions from residential coal and low-smoke fuels, using CMD modelling, in South Africa. *Environmental Science and Policy*, 5(2):157-167.
- Environmental Assurance (ENVASS). 2017. Introduction of local Air Quality Management in South Africa: Overview and challenges. URL: <http://www.envass.co.za/introduction-of-local-air-quality-management-in-south-africa-overview-and-challenges/> Date of Access: 10 August 2018.
- EPA. 2000. Compilation of air pollution emission factors (AP-42), as contained in the AirCHIEF (Air Clearinghouse for Inventories and Emission Factors) data base, US Environmental Protection Agency (EPA), Research Triangle Park, North Carolina.

- Eskom. 1998. Eskom environmental report. Eskom, Johannesburg.
- Esmen, N.A. & Marsh, G.M. 1996. Applications and limitations of air dispersion modelling in environmental epidemiology. *Journal of Exposure Analysis and Environmental Epidemiology*, 6(3):339-353.
- Etyemezian, V., Tesfaye, M., Yimer, A., Chow, J.C., Mesfin, D. & Nega, T. 2005. Results from a pilot-scale air quality study in Addis Ababa, Ethiopia. *Atmospheric Environment*, 39:7849-60.
- Faulkner, W.B., Shaw, B.W. & Grosch. 2008. Sensitivity of two dispersion models (AERMOD and ISCST3) to input parameters for rural ground-level area source. *Journal of the Air & Waste Management Association*, 58(10):1288-1296.
- Fenger, J. 1999. Urban air quality. *Atmospheric Environment*, 33(29):4877-4900.
- Fenger, J. 2009. Air pollution in the last 50 years – from local to global. *Atmospheric Environment*, 43(1):13-22.
- Fisher, T.E. & Sánchez Piña, A.L. 2013. *Dioxin emissions from municipal waste burning in South Africa: Development of a GIS-based emissions inventory*. Paper presented at the 16th IUAPPA World Clean Air Congress, Cape Town, 29 Sep-04 Oct.
- Freiman, M.T. & Piketh, S.J. 2002. Air Transport into and out of the Industrial Highveld Region of South Africa. *Journal of Applied Meteorology*, 42:994-1002.
- FRIDGE. 2004. Study to examine the potential socio-economic impact of measures to reduce air pollution from combustion. Airshed Planning Professionals and Bentley West Management. Consultants for Trade and Industry Chamber / Fund for Research into Industrial Development, Growth and Equity (FRIDGE), Johannesburg.
- Frohn, L.M., Christensen, J.H. & Brandt, J. 2002. Development of a high-resolution nested air pollution model. *Journal of Computational Physics*, 179(1):68-94.
- Garmichael, G.R., Tang, Y., Kurata, G., Uno, I., Streets, D.G., Thongboonchoo, N., Woo, J.H., Guttikunda, S., White, A., Wang, T., Blake, D.R., Atlas, E., Fried, A., Potter, B., Avery, M.A., Sachse, G.W., Sandholm, S.T., Kondo, Y., Talbot, R.W., Bandy, A., Thornton, D. & Clarke, A.D. 2003. Evaluating regional emission

estimates using TRACE-P observations. *Journal of Geophysical Research*, 108(D21):2156-2202.

Gierens, R.T., Laakso, L., Mogensen, D., Vakkari, V., Beukes, J.P., Van Zyl, P.G., Hakola, H., Guenther, A., Pienaar, J.J. & Boy, M. 2014. Modelling new particle formation events in the South African savannah. *South African Journal of Science*, 110(5-6):1-12.

Gifford, F.A. & Hanna, S.R. 1975. Modelling urban air pollution. *Atmospheric Environment*, 9(2):267-270.

Giovis, C. 2005a. A review and evaluation of intra-urban air pollution exposure models. *Journal of Exposure Analysis and Environmental Epidemiology*, 15:185-204.

Godwana Environmental Solutions. 2016. South Africa's Air Quality Act. URL: <http://www.gondwanagroup.co.za/south-africas-air-quality-act/> Date of access: 10 August 2018.

Gordon, G.E. 1988. Receptor models. *Environmental Science and Technology*, 22(10):1132-1142.

Gryning, S.E., Holtslag, A.A.M., Irwin, J.S. & Sivertsen, B. 1987. Applied dispersion modelling based on meteorological scaling parameters. *Atmospheric Environment*, 21(1):79-89.

Hall, J.D., Spanton, A.M., Dunkerley, F., Bennet, M. & Griffiths. 2000. A review of dispersion model inter-comparison studies using ISC, R91, AERMOD and ADMS. R&D Technical Report P353. Bristol: Environmental Agency.

Hales, S., Salmond, C., Town, G.I., Kjellstrom, T. & Woodward, A. 2000. Daily mortality in relation to weather and air pollution in Christchurch, New Zealand. *Australian and New Zealand Journal of Public Health*, 24(1):89-91.

Hanna, R.S., Paine, R., Heinold, D., Kintigh, E. & Baker, D. 2007. Uncertainties in air toxics calculated by dispersion Models AERMOD and ISCST3 in the Houston ship channel area. *Journal of Applied Meteorology and Climatology*, 46:1372-1382.

Harré, E.S., Price, P.D., Ayrey, R.B., Toop, L.J., Martinl, R. & Town, G.I. 1997. Respiratory effects of air pollution in chronic obstructive pulmonary disease: A three month prospective study. *Thorax*, 52(12):1040-1044.

- Harrison, R.M. & Yin, J. 2000. Particulate matter in the atmosphere: which particle properties are important for its effects on health? *The Science of the Total Environment*, 249:85-101.
- Held, G., Gore, B.J., Surridge, A.D., Tosen, G.R., Turner, C.R. & Walmsley, R.D. 1996. Air pollution and its Impacts on the South African Highveld. Environmental Scientific Association, Cleveland, 144 pp.
- Hersey, S.P., Piketh, S.J. & Burger, R.P. 2014. A comprehensive study of air quality in urban, low-income areas of South Africa. Paper presented at the 30th Annual Conference of the South African Society for Atmospheric Sciences, 1-2 Oct. 2014, Potchefstroom, South Africa.
- Hou, Q., An, X.Q., Wang, Y. & Guo, J.P. 2010. An evaluation of resident exposure to respirable particulate matter and health economic loss in Beijing during Beijing 2008 Olympic Games. *Science of the Total Environment*, 408:4026-4032.
- Hunter, D., Sulzman, J. & Zaelke, D. 2002. International Environmental Law and Policy. Foundation Press, New York.
- Jackson, M.M. 2005. Roadside concentration of gaseous and particulate matter pollutants and risk assessment in Dar-es-Salaam, Tanzania. *Environmental Monitoring Assessment*, 104:385-407.
- Jerrett M., Burnett R.T., Kanaroglou P., Eyles J., Finkelstein, N., Giovis, C. & Brook J.R. 2001. A GIS- environmental justice analysis of particulate air pollution in Hamilton, Canada. *Environment and Planning*, (33):955-973.
- Jerret, M., Arain, A., Kanaroglou, P., Beckerman, B., Potoglou, D., Sahuvaroglu, T., Morrison, J. & Giovis, C. 2005. A review and evaluation of intra-urban pollution exposure models. *Journal of Exposure Science & Environmental Epidemiology*, 15:185-204.
- Johnson, C., Henkshaw, J. & McLnnes, G. 1992. Impact of aircraft and surface emissions of nitrogen oxides and tropospheric ozone and global warming. *Nature*, 355:69-71.
- Jorgensen, M.W. & Sorenson, S.C. 1997. Estimating emissions from railway traffic, report for the project MEET: methodologies for estimating air pollutant emissions

from transport, funded by the European Commission under the Transport RTD Program of the 4th Framework Program, Report No. ET-EO-97-03, July.

Josipovic, M., Venter, Vakkari, V., Beukes, J.P., Van Zyl, P.G., Laakso, H., Mabaso, D., Tiitta, P., Kulmala, M., Pienaar, J.J. & Laakso, L. 2012. Air Quality assessment in the industrialised western Bushveld Igneous Complex, South Africa. *South African Journal of Science*, 108:1-10.

Kesarkar, P.A., Dalvi, M., Kaginalkar, A. & Ojha, A. 2007. Coupling of the weather research and forecasting model with AERMOD for pollutant dispersion modelling: A case study for PM₁₀ dispersion over Pune, India. *Atmospheric Environment*, 41:1976-1988.

Kleeman, M.J. & Cass, G.R. 1998. Source contributions to the size and composition distribution of urban particulate air pollution. *Atmospheric Environment*, 32(16):2803-2816.

Koppman, R., von Czapiewski, K. and Reid, J. S. 2005. A review of Biomass Burning Emissions, Part 1: Gaseous Emissions of Carbon monoxide, Methane, Volatile Organic Compounds and Nitrogen Containing Compounds. *Atmospheric Chemistry and Physics Discussions*, 5(5):10455-10516.

Korczyk, M., Fudała, J. & Kliś, C. 2009. Estimation of windblown dust emissions in Europe and its vicinity. *Atmospheric Environment*, 43(7):1410 -1420.

Kornelius, G., Kruger, S., Fouchee, R. & van Wyk, H. 2012. A wood gasification stove for domestic use: design, performance and emission factors. National Association of Clean Air. *The Clean Air Journal*, 22(2):14-16.

Kornelius G., Sithole A., Kruger S., Fouchee R. & van Wyk H. 2013. A wood gasification stove for domestic use: Performance and emission factors using locally available fuel'. Presented at IUAPPA World Clean Air Congress in 2013, Cape Town, South Africa.

Kumar, A., Dixit, S., Varadarajan, C., Vijayan, A. & Masuraha, A. 2006. Evaluation of the AERMOD dispersion model as a function of atmospheric stability for an urban area. Department of Civil Engineering, University of Toledo. Ohio: Wiley InterScience.

- Langer, C. & Klemm, O. 2011. A comparison of model performance between AERMOD and AUSTAL2000. *Journal of the Air and Waste Management Association*, 61(6):640-646.
- Leaner, J.J., Dabrowski, J.M., Mason, R.P., Resane, T., Richardson, M., Ginster, M., Gericke, Gerhard, G., Peterson, C.R., Masekoameng, E., Ashton, P.J. & Murray, K. 2009. Mercury Emissions from Point Sources in South Africa. In: (Eds. Pirrone, N. & Mason, R.), Springer Science + Business Media, LLC, 2009.
- Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D. & Pozzer, A. 2015. The Contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, 525(7569):367-371.
- Liousse, C., Assamoi, E., Criqui, P., Granier, C. & Rosset, R. 2014. Explosive growth in African combustion emissions from 2005 to 2013. *Environmental Research Letters*, 9(3):1-10.
- Liousse C., Penner, J.E., Chuang, C., Walton, J.J., Eddleman, H. & Cachier, H. 1996. A global three-dimensional model study of carbonaceous aerosols. *Journal of Geophysical Research: Atmospheres*, 101(D14):19411-19432.
- Liousse, C., Guillaume, B., Grégoire, J.M., Mallet, M., Galy, C., Pont, V., Akpo, A., Bedou, M., Castéra, P., Dungall, L., Gardrat, E., Granier, C., Konaré, A., Malavelle, F., Mariscal, A., Mieville, A., Rosset, R., Serça, D., Solmon, F., Tummon, F., Assamoi, E., Yoboué, V. & Van Velthoven, P. 2010. Updated African biomass burning emission inventories in the frame of the AMMA-IDAF program, with an evaluation of combustion aerosols. *Atmospheric Chemistry Physics*, 10(19):7347-7382.
- Lloyd, P.J.D. 2006. The saga of the paraffin stove: Chemical engineering at the poverty line, SAChE Chemical Engineering Congress, Durban.
- Lourens, A.S., Beukes, J.P., Van Zyl, P.G., Fourie, G.D., Burger, J. W., Pienaar, J.J., Read, C.E. & Jordaan, J.H. 2011. Spatial and temporal assessment of gaseous pollutants in the Highveld of South Africa. *South African Journal of Science*, 107(1/2):1-8.
- Lvovsky, K., Hughes, G., Maddison, D., Ostro, B. & Pearce, D. 2000. Environmental costs of fossil fuels: a rapid assessment method with application to six cities.

World Bank, Washington, DC.
<https://openknowledge.worldbank.org/handle/10986/18303> Date of access: 19 Jan. 2015.

- Mage, D., Ozolins, G., Peterson, P., Webster, A., Orthofer, R., Vandeweerd, V. & Gwynne, M. 1996. Urban air pollution in megacities of the world. *Atmospheric Environment*, 30(5):681-686.
- Makonese, T., Masekameni, DM., Annegarn, H.J. & Forbes, P.B.C. 2016. Emission factors of domestic coal-burning braziers. *South African Journal of Science*, 113(3/4).
- Mayer, H. 1999. Air pollution in cities. *Atmospheric Environment*, 33(24-25):4029-4037.
- Mdluli, T.N. 2007. The societal dimensions of domestic coal combustion: people's perceptions and indoor aerosol monitoring. Johannesburg: University of Johannesburg (Thesis – PhD).
- Morgan, G.B. 1997. Ambient air quality. (In monitoring methods and standards for environmental measurement: proceedings of the 8th materials research symposium held at the National Bureau of Standards, Gaithersburg, Maryland, September 20-24, 1976, Issue 464).
- Moussiopoulos, N., Schlünzen, H. & Louka, P. 2003. Air quality in cities: modelling urban air pollution. 1st ed. London: Springer Berlin Heidelberg.
- Mukala K., Alm S., Tiittanen P., Salonen R.O., Jantunen M. & Pekkanen, J. 2000. Nitrogen dioxide exposure assessment and cough among preschool children. *Archives of Environmental Health*, 55(6):431-438.
- Naeher, L., Brauer, M., Lipsett, M., Zelikoff, J., Simpson, C., Koenig, J. & Smith, K. 2007. Wood smoke health effects: A review. *Inhalation Toxicology: International Forum for Respiratory Research*, 19(1):67-106.
- Naidoo, S., Piketh, S.J. & Curtis, C. 2014. Quantification of emissions generated from domestic burning activities from townships in Johannesburg. *Clean Air Journal*, 24(1):34-41.

- National Environmental Management: Air Quality Act 39 of 2004. https://www.environment.gov.za/sites/default/files/gazetted_notices/nema_national_framework_aqm_gn115.pdf Date of access: 1 June 2015.
- National Research Council (NRC). 1991. Rethinking the Ozone Problem in Urban and Regional Pollution. Washington, D.C.: National Academy Press.
- Norman R., Cairncross, E., Witi, J., Bradshaw, D. & The South African Comparative Risk Assessment Collaborating Group. 2007. Estimating the burden of disease attributable to urban outdoor air pollution in South Africa in 2000. *South African Medical Journal*, 97(8):782-790.
- Oke, T.R. 1982. The energetic basis of the urban heat island. *Quarterly Journal of Royal Meteorology Society*, 108:1-24.
- Omstedta, G., Bringfelb, B. & Johanssonc, C. 2005. A model for vehicle-induced non-tailpipe emissions of particles along Swedish roads. *Atmospheric Environment*, 39(33):6088-6097.
- Paumier, J.O. & Brode, R.W. 2004. User's guide for the AERMOD meteorological pre-processor (AERMET). U.S. Environmental Protection Agency, North Carolina, Report 68D70069.
- Pauw, C.J., Friedl, A., Holm, D., John, J., Kornelius, G., Oosthuizen, R. & van Niekerk, A.S. 2008. Air pollution in dense, low-income settlements in South Africa. Issue 1. Nova report to the Royal Danish embassy and the dept. of Environmental Affairs and Tourism. URL: www.zotero.org/groups/eheo/items/itemkey/IV6FAVBV. Date of access: 05 May 2015.
- Pauw, C. 2013. The elephant in the room: What do we know about urban wood use in South Africa? Paper presented at the 16th IUAPPA World Clean Air Congress, Cape Town, 29 Sep-04 Oct.
- Perry, S.G., Cimorelli, A.J., Paine, R.J., Brode, R.W., Weil, J.C., Venkatram, A., Wilson, R.B., Lee, R.F. & Peters, W.D. 2005. AERMOD: A dispersion model for industrial source applications. Part II: Model performance against 17 field study databases. *Journal of Applied Meteorology*, 44:694-708.

- Pielke, R.A. & Uliasz, M. 1998. Use of meteorological models as input to regional and meso-scale air quality models – limitations and strengths. *Atmospheric Environment*, 32(8):1455-1466.
- Pienaar, J.J. & Helas, G. 1996. The kinetics of chemical processes affecting acidity in the atmosphere. *South African Journal of Science*, 93(3):128-132.
- Piketh, S.J. & Annegarn, H.J. 1994. Dry deposition of sulphate aerosols and acid rain potential in the Eastern Transvaal and Lowveld Regions. Paper presented at the National Association for Clean Air Conference, Cape Town, 24-25 November.
- Piketh, S.J., Burger, R. & Pauw, C. 2013. Indoor household air pollution measurements from solid fuel (coal) combustion in Mpumalanga, South Africa. Cape Town: IUAPPA.
- Pope III, C.A., Burnett, R.T., Thun, M.J., Galle, E.E., Krewski, D., Ito, K. & Thurston, G.D. 2002. Lung cancer, cardiopulmonary mortality and long-term exposure to fine particulate air pollution. *American Medical Association*, 287(9):1132-1141.
- Pope III, C.A. & Dockery, D.W. 2006. Health effects of fine particulate air pollution: lines that connect. *Journal of the Air and Waste Management Association*, 56(6):709-742.
- Pope III, C.A., Ezzati, M. & Dockery, D.W. 2009. Fine-particulate air pollution and life expectancy in the United States. *The New England Journal of Medicine*, 10(360):376-386.
- Pretorius, I., Piketh, S.J., Burger, R.P. & Neomagus, H. 2015. South African coal-fired power station emissions: the past, the present and the future. *Journal of Energy in Southern Africa*, 26(3):27-40.
- Ramsay, L.F. 2008. Accepting poor Environmental Health. Presentation at RGS-IBG Annual Conference, University College London, 27-29 Aug.
- Roberts, E. & Wentzel, M. 2006. Household paraffin consumption in four areas: Benoni, Galeshewe, Gugulethu and Lady Grey. *Journal of Energy in Southern Africa*, 17(2):23-26.
- Rogers, A. & Williamson, J.G. 1982. Economic development and cultural change. *Chicago Journals*, 30(3):463-482.

- Sahsuvaroglu, T., Araina, A., Kanaroglou, P., Finkelstein, N., Newbold, B., Jerrett, M., Beckerman, B., Brooke, J., Finkelstein, M. & Gilbert, N.L. 2006. A land use regression model for predicting ambient concentrations of nitrogen dioxide in Hamilton, Ontario, Canada. *Journal of the Air & Waste Management Association*, 56(8):1059-1069.
- Saksena, S., Singh, P.B., Prasad, R.K., Prasad, R., Malhotra, P. & Joshi, V. 2003. Exposure of infants to outdoor and indoor air pollution in low-income urban areas: A case study of Delhi. *Journal of Exposure Science & Environmental Epidemiology*, 13:219-230.
- Saltelli, A., Tarantola, S. & Chan, K.P.S. 2012. A quantitative model-independent method for global sensitivity analysis of model output. *Techno-metrics*, 41(1):39-56.
- Schauer, J.J., Rogge, W.F., Hildemann, L.M., Mazurek, M.A. & Cass, G.R. 1996. Source apportionment of airborne particulate matter using organic compounds and tracers. *Atmospheric Environment*, 30(22):3837-3855.
- Schwartz, J., Slater, D., Larson, T.V., Pierson, W.E. & Koenig, J.Q. 1993. Particulate air pollution and hospital emergency room visits for asthma in Seattle. *American Review of Respiratory Disease*, 147(4):826-831.
- Scorgie, Y., Kneen, M.A., Annegarn, H.J. & Burger, L.W. 2003. Air pollution in the Vaal Triangle – Quantifying source contributions and identifying cost: Effective solutions. *Clean Air Journal*, 13(4):5-18.
- Scorgie, Y., Burger, L., Annegarn, H. & Kneen, M. 2004. Fund for research into industrial development growth and equity (FRIDGE). Part 2 Report: Establishment of Source Inventories and Identification and Prioritisation of Technology Options.
- Scorgie, Y. & Kornelius, G. 2009. Modelling of acid deposition over the South African Highveld. Paper presented at the annual South African National Association for Clean Air Conference, 14-16 Oct. 2009, Vanderbijlpark, South Africa.
- Scorgie, Y. 2012. Urban air quality and planning in South Africa. Johannesburg: University of Johannesburg (Thesis – PhD).

- Schwela, D. 2004. Air Quality Management: Sustainable Transport: A Sourcebook for Policy Makers in Developing Cities: Module 5.
- Seangkiatiyuth, K., Surapipith, V., Tantrakarnapa, K. & Lothongkum. 2011. Application of the AERMOD modelling system for environmental impact assessment of NO₂ emissions from a cement complex. *Journal of Environmental Sciences*, 23(6):931-940.
- Seaton, A., MacNee, W., Donaldson, K. & Golden, D. 1995. Particulate air pollution and acute health effects. *Lancet*, 345:176-178.
- Sheppard, L., Levy, D., Noms, G., Larson, I.V. & Koenig, J.Q. 1999. Effects of ambient pollution on non-elderly asthma hospital admissions in Seattle, Washington, 1987-1994. *Epidemiology*, 10(1):23-30.
- Shirinde, J., Wichmann, J. & Voyi, K. 2014. Association between wheeze and selected air pollution sources in an air pollution priority area in South Africa: a cross-sectional study. *Environmental Health*, 13(32).
- Snyman, C.P. & Botha, W.J. 2003. Coal in South Africa. *Journal of African Earth Sciences (and the Middle East)*, 16(1-2):171-180.
- South Africa. Department of Environmental Affairs. 2006. Atmospheric modelling. Series B: Book 3. Pretoria.
- South Africa. Department of Environmental Affairs. 2007. Indoor air quality. Pretoria.
- South Africa. Department of Minerals and Energy. 2000. Energy balances for South Africa 1993-98. Pretoria.
- South Africa. 2009. National Environmental Management: Air Quality Act 39 of 2004: National Ambient Air Quality Standards. Government Gazette, 32816:532, 24 Dec.
- South Africa. 2012. National Environmental Management: Air Quality Act 39 of 2004: National Ambient Air Quality Standards. Government Gazette, 35463:7, 29 Jun.
- South Africa. 2014. National Environmental Management: Air Quality Act 39 of 2004: Regulations Regarding Air Dispersion Modelling. 2014, Government Gazette, 37804:75, 11 Jul.

- South Africa. Department of Economic Development, Environment and Tourism. . 2011. Ambient Air Quality Monitoring Network in Mpumalanga Province. URL: <http://www.airqualityilekgotla.co.za/assets/2.2-ambient-aqm-in-mpumalanga.pdf> Date of Access: 17 June 2019.
- South Africa. Department of Energy. 2018. Energy Sources. URL: http://www.energy.gov.za/files/petroleum_frame.html Date of Access: 10 August 2018.
- Spalding-Fecher, R. & Matibe, D.K. 2003. Electricity and externalities in South Africa. *Energy Policy*, 31:721-734.
- Statistics South Africa (SSA). Census 2011: Statistical release. Technical Report P0301.4, Statistics South Africa, October 2012.
- Statistics South Africa, (SSA). 2014. Poverty trends in South Africa: An examination of absolute poverty between 2006 and 2011. URL: <http://beta2.statssa.gov.za/publications/Report-03-10-06/Report-03-10-06March2014.pdf> Date of access: 18 December 2014.
- Statistics South Africa (SSA). 2016. Community Survey, 2016 – P0301. URL: http://cs2016.statssa.gov.za/wp-content/uploads/2016/07/NT-30-06-2016-RELEASE-for-CS-2016-_Statistical-releas_1-July-2016.pdf Date of access: 10 August 2018.
- Stein, A.F., Isakov, V., Godowitch, J. & Draxler, R.R. 2007. A hybrid modelling approach to resolve pollutant concentrations in an urban area. *Atmospheric Environment*, 41(40):9410-9426.
- Streets, D. G., Bond, T.C., Carmichael, G.R., Fernandes, S.D., Fu, Q., He, D., Klimont, Z., Nelson, S.M., Tsai, N.Y., Wang, M.Q., Woo, J.-H. & Yarber, K.F. 2003. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. *Journal of Geophysical Research: Atmospheres*, 108(D21):2156-2202.
- Strydom, H.A. & King, N.D. 2009. Environmental Management in South Africa. 2nd ed. Cape Town: JUTA Law.
- Sun, Y., Zhuang, G., Wang, Y., Han, L., Guo, J., Dan, M., Zhang, W., Wang, Z. & Hao, Z. 2004. The air-borne particulate pollution in Beijing: Concentration,

composition, distribution and sources. *Atmospheric Environment*, 38(35):5991-6004.

Taylor, K.E. 2001. Summarizing multiple aspects of model performance in a single diagram. *Journal of Geophysical Research*, 106:7183-7192.

Terblanche, P., Nel, R., Reinach, G. & Opperman, L. 1992. Personal exposures to total suspended particulates from domestic coal burning in South Africa. *Clean Air Journal*, 8(6):15-17.

Thambiran, T. & Diabb, R.D. 2011. Air pollution and climate change co-benefit opportunities in the road transportation sector in Durban, South Africa. *Atmospheric Environment*, 45(16):2683-2689.

The World Bank. 2015. Urban population (% of total). <http://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS> Date of access: 22 Apr. 2015.

The World Bank. 2016. Energy. <http://www.worldbank.org/en/topic/energy> Date of access: 4 Apr. 2017.

Thurston, G.D., Ito, K., Mar, T., Christensen, W.F., Eatough, D.J., Henry, R.C., Kom, E., Laden, F., Lall, R., Larson, T.V., Liu, H., Neas, L., Pinto, J., Stölzel, M., Suh, H. & Hopke, P.K. 2005. Workgroup Report: Workshop on source apportionment of particulate matter health effects: Inter-comparison of results and implications. *Environmental Health Perspective*, 113(12):1768-1774.

Thurston, G.D. & Spengler, J.D. 1985. A quantitative assessment of source contributions to inhalable particulate matter pollution in metropolitan Boston. *Atmospheric Environment*, 19(1):9-25.

Tilmes, S., Brandt, J., Flatoy, F., Bergstrom, R., Flemming, J., Langner, J., Christensen, J.H., Frohn, L.M., Hov, O., Jacobsen, I., Reimer, E., Stem, R. & Zimmermann, J. 2002. Comparison of five Eulerian air pollution forecasting systems for the summer of 1999 using the German ozone monitoring data. *Journal of Atmospheric Chemistry*, 42:91-121.

Treets, D.G., Yarber, K.F., Woo, J.H. & Carmichael, G.R. 2003. Biomass burning in Asia: Annual and seasonal estimates and atmospheric emissions. *Global Biogeochemical Cycles*, 17(4):1-20.

- US Environmental Protection Agency. 1994. AP-42 Volume 1 – Introduction. URL: <http://www.epa.gov/ttnchie1/ap42/c00s00.pdf> Date of access: 28/08/2015.
- US Environmental Protection Agency. 2004. User's Guide for the AMS/EPA Regulatory Model—AERMOD, EPA-454/B-03-001, Research Triangle Park, NC 27711.
- US Environmental Protection Agency. 2015. Ambient Air Monitoring and Emissions Measurement. URL: <http://www.epa.gov/airquality/aqportal/management/monitoring.htm> Date of access: 12 Sep. 2015.
- Vakkari, V., Kerminen, V., Beukes, J.P., Titta, P., van Zyl, P.G., Josipovic, M., Venter, A.D., Jaars, K., Worsnop, D.R., Kulmala, M. & Laakso, L. 2014. Rapid changes in biomass burning aerosols by atmospheric oxidation, *Geophysical Research Letters*, 41(7):2644-2651.
- Van den Berg, B., Piketh, S.J., Burger, R., Pauw, C.J. & Hersey, S.P. 2014. Domestic fuel use in South African low-income settlements. Paper presented at National Association for Clean Air Annual Conference, Umhlanga, 08-10 Oct.
- Van Zyl, P.G., Beukes, J.P., du Toit, G., Mabaso, D., Hendriks, J., Vakkari, V., Tiita, P., Pienaar, J.J., Kulmala, M. & Laakso, L. 2014. Assessment of atmospheric trace metals in the western Bushveld Igneous Complex, South Africa. *South African Journal of Science*, 110(3):1-10.
- Venn, A.J., Lewis, S.A., Cooper, M., Hubbard R. & Britton, J. 2001. Living near a main road and the risk of wheezing illness in children. *American Journal of Respiratory and Critical Care Medicine*, 164(12):2177-2180.
- Venkatram, A., Isakov, V., Yuan, J. & Pankratz. 2004. Modelling dispersion at distances of meters from urban sources. *Atmospheric Environment*, 38(28):4633-4641.
- Weil, J.C., Sykes, S.I. & Venkatram, A. 1992. Evaluating air quality models: Review and outlook. *Journal of Applied Meteorology*, 31:1121-1145.
- Wheeler, A.J., Smith-Doiron, M., Xu, X., Gilbert, N.L. & Brook, J.R. 2008. Intra-urban variability of air pollution in Windsor, Ontario: Measurement and modelling for human exposure assessment. *Environmental Research*, 106(1):7-16.

- World Health Organization. 2013. Health effects of particulate matter: Policy implications for countries in Eastern Europe, Caucasus and central Asia. URL: http://www.euro.who.int/__data/assets/pdf_file/0006/189051/Health-effects-of-particulate-matter-final-Eng.pdf Date of access: 2 May 2015.
- World Health Organisation. 2014. Urban population growth. http://www.who.int/gho/urban_health/situation_trends/urban_population_growth_text/en/ Date of access: 1 Dec. 2014.
- Worobiec, A., Potgieter-Vermaak, S.S., Berghmans, P., Winkler, H., Burger, R. & Van Grieken, R. 2011. Air particulate emissions in developing countries: A case study in South Africa. *Analytical Letters*, 44:1907-1924.
- Xu, X., Gaoc, J. & Chenc, Y. 1994. Air pollution and daily mortality in residential areas of Beijing, China. *Archives of Environmental Health: An International Journal*, 49(4):216-222.
- Xu, Z., Yu, D., Jing, L. & Xu, X. 2000. Air pollution and daily mortality in Shenyang, China. *Archives of Environmental Health: An International Journal*, 55(2):115-120.
- Yu, O., Sheppard, L., Lumley, T., Koenig, J.Q. & Shapiro, G.G. 2000. Effects of ambient air pollution on symptoms of asthma in Seattle-area children enrolled in the CAMP study. *Environmental Health Perspective*, 108(12):1209-1214.
- Yuan, B. & Dong, D. 2006. Accounting of health-loss value induced by inhalable particulate matter: A case study of Jilin City. *Sichuan Environment*, 25(2):84-86.
- Zhao, D. & Sun, B. 2012. Atmospheric pollution from coal combustion in China. *Journal of Air Pollution Control Association*, 36(4):371-374.
- Zannetti, P. 1993. Numerical simulation modelling of air pollution: an overview, in Air Pollution. *Computational Mechanics Publications, Southampton*, p.3-14.
- Zhang, J. & Smith, K.R. 2007. Household air pollution from coal and biomass fuels in China: measurements, health impacts, and interventions. *Environmental Health Perspective*, 115(6):848-855.

Zheng, M., Salmon, L.G., Schauer, J.J., Zeng, L., Kiang, C.S. & Zhang, Y. 2005. Seasonal trends in PM_{2.5} source contributions in Beijing, China. *Atmospheric Environment*, 39:3967-3976.

Zhou, Y., Levy, J.I., Hammitt, J.K. & Evans, J.S. 2003. Estimating population exposure to power plant emissions using CALPUFF: a case study in Beijing, China. *Atmospheric Environment*, 37(6):815-826.

ANNEXURES

APPENDIX A.

AERMOD OUTPUT SUMMARY FILE – CHAPTER 3, MODEL RUN 1

*** AERMOD - VERSION 14134 ***

*** AERMET - VERSION 14134

PAGE 1

**MODELOPTs: RegDFault CONC ELEV FLGPOL VectorWS

*** MODEL SETUP OPTIONS SUMMARY ***

**Model Is Setup For Calculation of Average CONCentration Values.

-- DEPOSITION LOGIC --

**NO GAS DEPOSITION Data Provided.

**NO PARTICLE DEPOSITION Data Provided.

**Model Uses NO DRY DEPLETION. DRYDPLT = F

**Model Uses NO WET DEPLETION. WETDPLT = F

**Model Uses RURAL Dispersion Only.

**Model Uses Regulatory DEFAULT Options:

1. Stack-tip Downwash.
2. Model Accounts for ELEVated Terrain Effects.
3. Use Calms Processing Routine.
4. Use Missing Data Processing Routine.
5. No Exponential Decay.

**Other Options Specified:

VECTORWS - User specifies that input wind speeds are VECTOR means

CCVR_Sub - Meteorological data includes CCVR substitutions

TEMP_Sub - Meteorological data includes TEMP substitutions

**Model Accepts FLAGPOLE Receptor Heights.

**The User Specified a Pollutant Type of: PM_10

**Model Calculates 2 Short Term Average(s) of: 1-HR 24-HR

**This Run Includes: 1 Source(s); 1 Source Group(s); and 2503 Receptor(s)

**Model Set To Continue RUNning After the Setup Testing.

**The AERMET Input Meteorological Data Version Date: 14134

**Output Options Selected:

Model Outputs Tables of Highest Short Term Values by Receptor (RECTABLE Keyword)

Model Outputs Tables of Overall Maximum Short Term Values (MAXTABLE Keyword)

Model Outputs Tables of Concurrent Short Term Values by Receptor for Each Day Processed (DAYTABLE Keyword)

Model Outputs External File(s) of Threshold Violations (MAXIFILE Keyword)

Model Outputs External File(s) of High Values for Plotting (PLOTFILE Keyword)

Model Outputs External File(s) of Values by Season and Hour-of-Day (SEASONHR Keyword)

Model Outputs External File(s) of Ranked Values (RANKFILE Keyword)

Model Outputs Separate Summary File of High Ranked Values (SUMMFILE Keyword)

12 01 01	1 07	22.0	0.454	0.585	0.005	268.	733.	-313.2	0.10	0.40	0.30	5.10	355.	10.0	290.8	2.0
12 01 01	1 08	62.5	0.427	1.026	0.005	509.	671.	-91.9	0.10	0.40	0.21	4.60	303.	10.0	292.8	2.0
12 01 01	1 09	100.4	0.437	1.357	0.005	734.	693.	-61.2	0.10	0.40	0.19	4.60	277.	10.0	294.2	2.0
12 01 01	1 10	131.4	0.484	1.629	0.005	970.	806.	-63.3	0.10	0.40	0.18	5.10	271.	10.0	296.6	2.0
12 01 01	1 11	151.8	0.576	1.841	0.005	1210.	1047.	-92.4	0.10	0.40	0.18	6.20	274.	10.0	296.1	2.0
12 01 01	1 12	160.8	0.537	1.991	0.005	1445.	948.	-70.9	0.10	0.40	0.18	5.70	256.	10.0	298.4	2.0
12 01 01	1 13	155.6	0.488	2.042	0.007	1612.	822.	-54.9	0.10	0.40	0.18	5.10	263.	10.0	297.9	2.0
12 01 01	1 14	137.9	0.485	1.996	0.007	1695.	811.	-60.7	0.10	0.40	0.18	5.10	269.	10.0	297.4	2.0
12 01 01	1 15	120.7	0.611	1.932	0.007	1758.	1144.	-138.6	0.10	0.40	0.18	6.70	262.	10.0	297.2	2.0
12 01 01	1 16	96.2	0.565	1.808	0.008	1808.	1024.	-137.9	0.10	0.40	0.19	6.20	244.	10.0	298.2	2.0
12 01 01	1 17	58.1	0.516	1.536	0.008	1835.	892.	-173.1	0.10	0.40	0.21	5.70	251.	10.0	297.4	2.0
12 01 01	1 18	28.6	0.415	1.215	0.008	1843.	651.	-183.7	0.10	0.40	0.28	4.60	237.	10.0	294.8	2.0
12 01 01	1 19	-20.2	0.379	-9.000	-9.000	-999.	561.	198.1	0.10	0.40	0.55	4.60	254.	10.0	293.8	2.0
12 01 01	1 20	-31.0	0.365	-9.000	-9.000	-999.	530.	115.9	0.10	0.40	1.00	4.60	277.	10.0	292.8	2.0
12 01 01	1 21	-31.8	0.364	-9.000	-9.000	-999.	528.	111.9	0.10	0.40	1.00	4.60	340.	10.0	291.9	2.0
12 01 01	1 22	-27.9	0.315	-9.000	-9.000	-999.	425.	82.1	0.10	0.40	1.00	4.10	112.	10.0	291.4	2.0
12 01 01	1 23	-28.1	0.314	-9.000	-9.000	-999.	423.	81.3	0.10	0.40	1.00	4.10	40.	10.0	289.2	2.0
12 01 01	1 24	-32.5	0.363	-9.000	-9.000	-999.	525.	108.6	0.10	0.40	1.00	4.60	30.	10.0	289.1	2.0

First hour of profile data

YR MO DY HR HEIGHT F WDIR WSPD AMB_TMP sigmaA sigmaW sigmaV
 12 01 01 01 10.0 1 51. 5.70 287.0 99.0 -99.00 -99.00

F indicates top of profile (=1) or below (=0)

*** AERMOD - VERSION 14134 ***
 *** AERMET - VERSION 14134 ***

PAGE 4

**MODELOPTs: RegDFault CONC ELEV FLGPOL VectorWS

*** THE SUMMARY OF HIGHEST 1-HR RESULTS ***

** CONC OF PM₁₀ IN MICROGRAMS/M³ **

GROUP ID OF TYPE GRID-ID	DATE AVERAGE CONC (YYMMDDHH)	NETWORK RECEPTOR (XR, YR, ZELEV, ZHILL, ZFLAG)
ALL HIGH 1ST HIGH VALUE IS	6.85032 ON 12080203:	AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20) GC UCART1
GC UCART1 HIGH 2ND HIGH VALUE IS	6.68171 ON 12080821:	AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)
GC UCART1 HIGH 3RD HIGH VALUE IS	5.10632 ON 12090820:	AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)
GC UCART1 HIGH 4TH HIGH VALUE IS	4.59471 ON 12030804:	AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)
GC UCART1 HIGH 5TH HIGH VALUE IS	4.48640 ON 12080204:	AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)
GC UCART1 HIGH 6TH HIGH VALUE IS	4.41203 ON 12090822:	AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)
GC UCART1 HIGH 7TH HIGH VALUE IS	4.34070 ON 12082017:	AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)
GC UCART1 HIGH 8TH HIGH VALUE IS	4.14168 ON 12090319:	AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)
GC UCART1 HIGH 9TH HIGH VALUE IS	4.11392 ON 12082018:	AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)
GC UCART1 HIGH 10TH HIGH VALUE IS	4.04687 ON 12082020:	AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)
GC UCART1 HIGH 25TH HIGH VALUE IS	3.39785 ON 12080820:	AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)

*** RECEPTOR TYPES: GC = GRIDCART

GP = GRIDPOLR
DC = DISCCART
DP = DISCPOLR

*** AERMOD - VERSION 14134 ***
*** AERMET - VERSION 14134 ***

PAGE 5

**MODELOPTs: RegDFAULT CONC ELEV FLGPOL VectorWS

*** THE SUMMARY OF HIGHEST 24-HR RESULTS ***

** CONC OF PM_10 IN MICROGRAMS/M**3

**

GROUP ID	DATE	NETWORK
OF TYPE GRID-ID	AVERAGE CONC (YYMMDDHH)	RECEPTOR (XR, YR, ZELEV, ZHILL, ZFLAG)

ALL HIGH 1ST HIGH VALUE IS	1.48265c ON 12082724: AT (765396.18, 7070119.37, 1701.30, 1701.30, 1.20)	GC UCART1
HIGH 2ND HIGH VALUE IS	1.20884 ON 12071924: AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)	GC UCART1
HIGH 3RD HIGH VALUE IS	1.16887 ON 12063024: AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)	GC UCART1
HIGH 4TH HIGH VALUE IS	1.13406 ON 12081924: AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)	GC UCART1
HIGH 5TH HIGH VALUE IS	1.12887 ON 12082024: AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)	GC UCART1
HIGH 6TH HIGH VALUE IS	1.11025 ON 12071024: AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)	GC UCART1
HIGH 7TH HIGH VALUE IS	1.10504 ON 12082924: AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)	GC UCART1
HIGH 8TH HIGH VALUE IS	1.10286 ON 12061224: AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)	GC UCART1
HIGH 9TH HIGH VALUE IS	1.03573 ON 12081424: AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)	GC UCART1
HIGH 10TH HIGH VALUE IS	1.02497 ON 12060624: AT (766046.18, 7070069.37, 1700.40, 1700.40, 1.20)	GC UCART1
HIGH 25TH HIGH VALUE IS	0.75632 ON 12070424: AT (765846.18, 7070119.37, 1701.50, 1701.50, 1.20)	GC UCART1

*** RECEPTOR TYPES: GC = GRIDCART
GP = GRIDPOLR
DC = DISCCART
DP = DISCPOLR

*** AERMOD - VERSION 14134 ***
*** AERMET - VERSION 14134 ***

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**MODELOPTs: RegDFAULT CONC ELEV FLGPOL VectorWS

*** Message Summary : AERMOD Model Execution ***

----- Summary of Total Messages -----

A Total of	0 Fatal Error Message(s)
A Total of	1 Warning Message(s)
A Total of	64 Informational Message(s)
A Total of	8784 Hours Were Processed
A Total of	64 Calm Hours Identified

A Total of 0 Missing Hours Identified (0.00 Percent)

***** FATAL ERROR MESSAGES *****
*** NONE ***

***** WARNING MESSAGES *****
CO W116 21 MODOPT: Vector Wind Speeds specified on MODELOPT Keyword VECTORWS

APPENDIX B.

AERMOD OUTPUT SUMMARY FILE – CHAPTER 3, MODEL RUN 2

*** AERMOD - VERSION 14134 ***

*** AERMET - VERSION 14134 ***

PAGE 1

**MODELOPTs: NonDEFAULT CONC ELEV FLGPOL BETA LW2 VectorWS

*** MODEL SETUP OPTIONS SUMMARY ***

**Model Is Setup For Calculation of Average CONCentration Values.

-- DEPOSITION LOGIC --

**NO GAS DEPOSITION Data Provided.

**NO PARTICLE DEPOSITION Data Provided.

**Model Uses NO DRY DEPLETION. DRYDPLT = F

**Model Uses NO WET DEPLETION. WETDPLT = F

**Model Uses URBAN Dispersion Algorithm for the SBL for 456 Source(s),

for Total of 1 Urban Area(s):

Urban Population = 6000.0 ; Urban Roughness Length = 1.000 m

**Model Allows User-Specified Options:

1. Stack-tip Downwash.
2. Model Accounts for ELEVated Terrain Effects.
3. Use Calms Processing Routine.
4. Use Missing Data Processing Routine.
5. No Exponential Decay.
6. Urban Roughness Length of 1.0 Meter Used.

**Other Options Specified:

LOWWIND2 - Use LowWind2 BETA option

VECTORWS - User specifies that input wind speeds are VECTOR means

CCVR_Sub - Meteorological data includes CCVR substitutions

TEMP_Sub - Meteorological data includes TEMP substitutions

**Model Accepts FLAGPOLE Receptor Heights.

**The User Specified a Pollutant Type of: PM_10

**Model Calculates 2 Short Term Average(s) of: 1-HR 24-HR

**This Run Includes: 456 Source(s); 1 Source Group(s); and 2503 Receptor(s)

**Model Set To Continue RUNning After the Setup Testing.

**The AERMET Input Meteorological Data Version Date: 14134

**Output Options Selected:

Model Outputs Tables of Highest Short Term Values by Receptor (RECTABLE Keyword)

Model Outputs Tables of Overall Maximum Short Term Values (MAXTABLE Keyword)

Model Outputs Tables of Concurrent Short Term Values by Receptor for Each Day Processed (DAYTABLE Keyword)

Model Outputs External File(s) of Threshold Violations (MAXIFILE Keyword)

Model Outputs External File(s) of High Values for Plotting (PLOTFILE Keyword)

Model Outputs External File(s) of Values by Season and Hour-of-Day (SEASONHR Keyword)

Model Outputs External File(s) of Ranked Values (RANKFILE Keyword)

Model Outputs Separate Summary File of High Ranked Values (SUMMFILE Keyword)

12 01 01	1 08	62.5	0.427	1.026	0.005	509.	671.	-91.9	0.10	0.40	0.21	4.60	303.	10.0	292.8	2.0
12 01 01	1 09	100.4	0.437	1.357	0.005	734.	693.	-61.2	0.10	0.40	0.19	4.60	277.	10.0	294.2	2.0
12 01 01	1 10	131.4	0.484	1.629	0.005	970.	806.	-63.3	0.10	0.40	0.18	5.10	271.	10.0	296.6	2.0
12 01 01	1 11	151.8	0.576	1.841	0.005	1210.	1047.	-92.4	0.10	0.40	0.18	6.20	274.	10.0	296.1	2.0
12 01 01	1 12	160.8	0.537	1.991	0.005	1445.	948.	-70.9	0.10	0.40	0.18	5.70	256.	10.0	298.4	2.0
12 01 01	1 13	155.6	0.488	2.042	0.007	1612.	822.	-54.9	0.10	0.40	0.18	5.10	263.	10.0	297.9	2.0
12 01 01	1 14	137.9	0.485	1.996	0.007	1695.	811.	-60.7	0.10	0.40	0.18	5.10	269.	10.0	297.4	2.0
12 01 01	1 15	120.7	0.611	1.932	0.007	1758.	1144.	-138.6	0.10	0.40	0.18	6.70	262.	10.0	297.2	2.0
12 01 01	1 16	96.2	0.565	1.808	0.008	1808.	1024.	-137.9	0.10	0.40	0.19	6.20	244.	10.0	298.2	2.0
12 01 01	1 17	58.1	0.516	1.536	0.008	1835.	892.	-173.1	0.10	0.40	0.21	5.70	251.	10.0	297.4	2.0
12 01 01	1 18	28.6	0.415	1.215	0.008	1843.	651.	-183.7	0.10	0.40	0.28	4.60	237.	10.0	294.8	2.0
12 01 01	1 19	-20.2	0.379	-9.000	-9.000	-999.	561.	198.1	0.10	0.40	0.55	4.60	254.	10.0	293.8	2.0
12 01 01	1 20	-31.0	0.365	-9.000	-9.000	-999.	530.	115.9	0.10	0.40	1.00	4.60	277.	10.0	292.8	2.0
12 01 01	1 21	-31.8	0.364	-9.000	-9.000	-999.	528.	111.9	0.10	0.40	1.00	4.60	340.	10.0	291.9	2.0
12 01 01	1 22	-27.9	0.315	-9.000	-9.000	-999.	425.	82.1	0.10	0.40	1.00	4.10	112.	10.0	291.4	2.0
12 01 01	1 23	-28.1	0.314	-9.000	-9.000	-999.	423.	81.3	0.10	0.40	1.00	4.10	40.	10.0	289.2	2.0
12 01 01	1 24	-32.5	0.363	-9.000	-9.000	-999.	525.	108.6	0.10	0.40	1.00	4.60	30.	10.0	289.1	2.0

First hour of profile data

YR MO DY HR HEIGHT F WDIR WSPD AMB_TMP sigmaA sigmaW sigmaV
 12 01 01 01 10.0 1 51. 5.70 287.0 99.0 -99.00 -99.00

F indicates top of profile (=1) or below (=0)

*** AERMOD - VERSION 14134 ***

*** AERMET - VERSION 14134 ***

PAGE 4

**MODELOPTs: NonDEFAULT CONC ELEV FLGPOL BETA LW2 VectorWS

*** THE SUMMARY OF HIGHEST 1-HR RESULTS ***

** CONC OF PM_10 IN MICROGRAMS/M**3 **

GROUP ID	DATE	NETWORK
OF TYPE GRID-ID	AVERAGE CONC (YYMMDDHH)	RECEPTOR (XR, YR, ZELEV, ZHILL, ZFLAG)

ALL HIGH 1ST HIGH VALUE IS	1.58344 ON 12080124: AT (765413.90, 7070618.04, 1710.00, 1710.00, 1.20)	GC UCART1
HIGH 2ND HIGH VALUE IS	1.53079 ON 12070504: AT (765413.90, 7070618.04, 1710.00, 1710.00, 1.20)	GC UCART1
HIGH 3RD HIGH VALUE IS	1.47511 ON 12031003: AT (765413.90, 7070618.04, 1710.00, 1710.00, 1.20)	GC UCART1
HIGH 4TH HIGH VALUE IS	1.45903 ON 12040506: AT (765413.90, 7070618.04, 1710.00, 1710.00, 1.20)	GC UCART1
HIGH 5TH HIGH VALUE IS	1.41797 ON 12041405: AT (765413.90, 7070618.04, 1710.00, 1710.00, 1.20)	GC UCART1
HIGH 6TH HIGH VALUE IS	1.41373 ON 12061618: AT (765413.90, 7070618.04, 1710.00, 1710.00, 1.20)	GC UCART1
HIGH 7TH HIGH VALUE IS	1.41187 ON 12031024: AT (765413.90, 7070618.04, 1710.00, 1710.00, 1.20)	GC UCART1
HIGH 8TH HIGH VALUE IS	1.41131 ON 12041906: AT (765413.90, 7070618.04, 1710.00, 1710.00, 1.20)	GC UCART1
HIGH 9TH HIGH VALUE IS	1.40810 ON 12060217: AT (765413.90, 7070618.04, 1710.00, 1710.00, 1.20)	GC UCART1
HIGH 10TH HIGH VALUE IS	1.40582 ON 12080123: AT (765413.90, 7070618.04, 1710.00, 1710.00, 1.20)	GC UCART1
HIGH 25TH HIGH VALUE IS	1.31790 ON 12080317: AT (765413.90, 7070618.04, 1710.00, 1710.00, 1.20)	GC UCART1

*** RECEPTOR TYPES: GC = GRIDCART
 GP = GRIDPOLR
 DC = DISCCART

DP = DISCPOLR

*** AERMOD - VERSION 14134 ***

*** AERMET - VERSION 14134 *** *** Kwadela PM10 Baserun

*** 04:54:46

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**MODELOPTs: NonDEFAULT CONC ELEV FLGPOL BETA LW2 VectorWS

*** THE SUMMARY OF HIGHEST 24-HR RESULTS ***

** CONC OF PM_10 IN MICROGRAMS/M**3 **

GROUP ID OF TYPE GRID-ID	DATE AVERAGE CONC (YYMMDDHH)	NETWORK RECEPTOR (XR, YR, ZELEV, ZHILL, ZFLAG)
-----------------------------	---------------------------------	---

ALL HIGH 1ST HIGH VALUE IS	0.66943 ON 12071024:	AT (766063.90, 7070418.04, 1706.50, 1706.50, 1.20) GC UCART1
GC UCART1 HIGH 2ND HIGH VALUE IS	0.64877 ON 12081024:	AT (766013.90, 7070368.04, 1704.50, 1704.50, 1.20)
GC UCART1 HIGH 3RD HIGH VALUE IS	0.60774 ON 12081424:	AT (766063.90, 7070168.04, 1703.00, 1703.00, 1.20)
GC UCART1 HIGH 4TH HIGH VALUE IS	0.56274 ON 12061224:	AT (766063.90, 7070168.04, 1703.00, 1703.00, 1.20)
GC UCART1 HIGH 5TH HIGH VALUE IS	0.54593 ON 12092724:	AT (766013.90, 7070168.04, 1703.00, 1703.00, 1.20)
GC UCART1 HIGH 6TH HIGH VALUE IS	0.53346 ON 12092624:	AT (765963.90, 7070168.04, 1703.00, 1703.00, 1.20)
GC UCART1 HIGH 7TH HIGH VALUE IS	0.52869 ON 12051924:	AT (766013.90, 7070118.04, 1701.90, 1701.90, 1.20)
GC UCART1 HIGH 8TH HIGH VALUE IS	0.52648 ON 12090924:	AT (766013.90, 7070168.04, 1703.00, 1703.00, 1.20)
GC UCART1 HIGH 9TH HIGH VALUE IS	0.52460 ON 12052924:	AT (766013.90, 7070168.04, 1703.00, 1703.00, 1.20)
GC UCART1 HIGH 10TH HIGH VALUE IS	0.51737 ON 12072024:	AT (766013.90, 7070168.04, 1703.00, 1703.00, 1.20)
GC UCART1 HIGH 25TH HIGH VALUE IS	0.47133 ON 12081024:	AT (766013.90, 7070118.04, 1701.90, 1701.90, 1.20)

*** RECEPTOR TYPES: GC = GRIDCART
 GP = GRIDPOLR
 DC = DISCCART
 DP = DISCPOLR

*** AERMOD - VERSION 14134 ***

*** AERMET - VERSION 14134 ***

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**MODELOPTs: NonDEFAULT CONC ELEV FLGPOL BETA LW2 VectorWS

*** Message Summary : AERMOD Model Execution ***

----- Summary of Total Messages -----

A Total of 0 Fatal Error Message(s)
 A Total of 5 Warning Message(s)
 A Total of 64 Informational Message(s)

A Total of 8784 Hours Were Processed

A Total of 64 Calm Hours Identified

A Total of 0 Missing Hours Identified (0.00 Percent)

***** FATAL ERROR MESSAGES *****
*** NONE ***

***** WARNING MESSAGES *****
CO W116 21 MODOPT: Vector Wind Speeds specified on MODELOPT Keyword VECTORWS
CO W122 21 MODOPT: LowWind2 Beta Option specified on MODELOPT Keyword Non-DEFAULT
CO W132 21 MODOPT: Minimum sigmav value (SVmin) for LowWind2 Beta Opt 0.3 m/s
CO W133 21 MODOPT: Maximum FRAN value (FRANmax) for LowWind2 Beta Opt 0.95
CO W320 23 URBOPT: Input Parameter May Be Out-of-Range for Parameter URB-POP

APPENDIX C.

AERMOD OUTPUT SUMMARY FILE – CHAPTER 3, MODEL RUN 3

*** AERMOD - VERSION 14134 ***

*** AERMET - VERSION 14134 ***

PAGE 1

**MODELOPTs: RegDEFAULT CONC ELEV FLGPOL VectorWS

*** MODEL SETUP OPTIONS SUMMARY ***

**Model Is Setup For Calculation of Average CONCentration Values.

-- DEPOSITION LOGIC --

**NO GAS DEPOSITION Data Provided.

**NO PARTICLE DEPOSITION Data Provided.

**Model Uses NO DRY DEPLETION. DRYDPLT = F

**Model Uses NO WET DEPLETION. WETDPLT = F

**Model Uses RURAL Dispersion Only.

**Model Uses Regulatory DEFAULT Options:

1. Stack-tip Downwash.
2. Model Accounts for ELEVated Terrain Effects.
3. Use Calms Processing Routine.
4. Use Missing Data Processing Routine.
5. No Exponential Decay.

**Other Options Specified:

VECTORWS - User specifies that input wind speeds are VECTOR means

CCVR_Sub - Meteorological data includes CCVR substitutions

TEMP_Sub - Meteorological data includes TEMP substitutions

**Model Accepts FLAGPOLE Receptor Heights.

**The User Specified a Pollutant Type of: PM_10

**Model Calculates 2 Short Term Average(s) of: 1-HR 24-HR

**This Run Includes: 1 Source(s); 1 Source Group(s); and 2503 Receptor(s)

**Model Set To Continue RUNning After the Setup Testing.

**The AERMET Input Meteorological Data Version Date: 14134

**Output Options Selected:

Model Outputs Tables of Highest Short Term Values by Receptor (RECTABLE Keyword)

Model Outputs Tables of Overall Maximum Short Term Values (MAXTABLE Keyword)

Model Outputs Tables of Concurrent Short Term Values by Receptor for Each Day Processed (DAYTABLE Keyword)

Model Outputs External File(s) of Threshold Violations (MAXIFILE Keyword)

Model Outputs External File(s) of High Values for Plotting (PLOTFILE Keyword)

Model Outputs External File(s) of Values by Season and Hour-of-Day (SEASONHR Keyword)

Model Outputs External File(s) of Ranked Values (RANKFILE Keyword)

Model Outputs Separate Summary File of High Ranked Values (SUMMFILE Keyword)

**NOTE: The Following Flags May Appear Following CONC Values: c for Calm Hours

m for Missing Hours

b for Both Calm and Missing Hours

**Misc. Inputs: Base Elev. for Pot. Temp. Profile (m MSL) = 3.00 ; Decay Coef. = 0.000 ; Rot. Angle = 0.0

12 01 01	1 09	100.4	0.437	1.357	0.005	734.	693.	-61.2	0.10	0.40	0.19	4.60	277.	10.0	294.2	2.0
12 01 01	1 10	131.4	0.484	1.629	0.005	970.	806.	-63.3	0.10	0.40	0.18	5.10	271.	10.0	296.6	2.0
12 01 01	1 11	151.8	0.576	1.841	0.005	1210.	1047.	-92.4	0.10	0.40	0.18	6.20	274.	10.0	296.1	2.0
12 01 01	1 12	160.8	0.537	1.991	0.005	1445.	948.	-70.9	0.10	0.40	0.18	5.70	256.	10.0	298.4	2.0
12 01 01	1 13	155.6	0.488	2.042	0.007	1612.	822.	-54.9	0.10	0.40	0.18	5.10	263.	10.0	297.9	2.0
12 01 01	1 14	137.9	0.485	1.996	0.007	1695.	811.	-60.7	0.10	0.40	0.18	5.10	269.	10.0	297.4	2.0
12 01 01	1 15	120.7	0.611	1.932	0.007	1758.	1144.	-138.6	0.10	0.40	0.18	6.70	262.	10.0	297.2	2.0
12 01 01	1 16	96.2	0.565	1.808	0.008	1808.	1024.	-137.9	0.10	0.40	0.19	6.20	244.	10.0	298.2	2.0
12 01 01	1 17	58.1	0.516	1.536	0.008	1835.	892.	-173.1	0.10	0.40	0.21	5.70	251.	10.0	297.4	2.0
12 01 01	1 18	28.6	0.415	1.215	0.008	1843.	651.	-183.7	0.10	0.40	0.28	4.60	237.	10.0	294.8	2.0
12 01 01	1 19	-20.2	0.379	-9.000	-9.000	-999.	561.	198.1	0.10	0.40	0.55	4.60	254.	10.0	293.8	2.0
12 01 01	1 20	-31.0	0.365	-9.000	-9.000	-999.	530.	115.9	0.10	0.40	1.00	4.60	277.	10.0	292.8	2.0
12 01 01	1 21	-31.8	0.364	-9.000	-9.000	-999.	528.	111.9	0.10	0.40	1.00	4.60	340.	10.0	291.9	2.0
12 01 01	1 22	-27.9	0.315	-9.000	-9.000	-999.	425.	82.1	0.10	0.40	1.00	4.10	112.	10.0	291.4	2.0
12 01 01	1 23	-28.1	0.314	-9.000	-9.000	-999.	423.	81.3	0.10	0.40	1.00	4.10	40.	10.0	289.2	2.0
12 01 01	1 24	-32.5	0.363	-9.000	-9.000	-999.	525.	108.6	0.10	0.40	1.00	4.60	30.	10.0	289.1	2.0

First hour of profile data

YR MO DY HR HEIGHT F WDIR WSPD AMB_TMP sigmaA sigmaW sigmaV
 12 01 01 01 10.0 1 51. 5.70 287.0 99.0 -99.00 -99.00

F indicates top of profile (=1) or below (=0)

*** AERMOD - VERSION 14134 ***
 *** AERMET - VERSION 14134 ***

PAGE 4

**MODELOPTs: RegDFAULT CONC ELEV FLGPOL VectorWS

*** THE SUMMARY OF HIGHEST 1-HR RESULTS ***

** CONC OF PM_10 IN MICROGRAMS/M**3 **

GROUP ID OF TYPE GRID-ID	DATE AVERAGE CONC (YYMMDDHH)	NETWORK RECEPTOR (XR, YR, ZELEV, ZHILL, ZFLAG)
ALL HIGH 1ST HIGH VALUE IS	1520.66104 ON 12080821: AT (	766001.02, 7069940.97, 1699.00, 1699.00, 1.20) GC UCART1
ALL HIGH 2ND HIGH VALUE IS	1180.98729 ON 12080203: AT (	765951.02, 7070040.97, 1699.00, 1699.00, 1.20) GC UCART1
ALL HIGH 3RD HIGH VALUE IS	1094.93484 ON 12091918: AT (	765801.02, 7069940.97, 1699.00, 1699.00, 1.20) GC UCART1
ALL HIGH 4TH HIGH VALUE IS	1056.39508 ON 12090820: AT (	765901.02, 7069940.97, 1699.00, 1699.00, 1.20) GC UCART1
ALL HIGH 5TH HIGH VALUE IS	1045.99675 ON 12090820: AT (	765901.02, 7069990.97, 1699.00, 1699.00, 1.20) GC UCART1
ALL HIGH 6TH HIGH VALUE IS	827.70307 ON 12082020: AT (	765951.02, 7069990.97, 1699.00, 1699.00, 1.20) GC UCART1
ALL HIGH 7TH HIGH VALUE IS	732.66748 ON 12060303: AT (	765601.02, 7069990.97, 1699.00, 1699.00, 1.20) GC UCART1
ALL HIGH 8TH HIGH VALUE IS	703.08059 ON 12030804: AT (	765951.02, 7069990.97, 1699.00, 1699.00, 1.20) GC UCART1
ALL HIGH 9TH HIGH VALUE IS	685.54836 ON 12082017: AT (	765951.02, 7070040.97, 1699.00, 1699.00, 1.20) GC UCART1
ALL HIGH 10TH HIGH VALUE IS	680.81790 ON 12082718: AT (	765601.02, 7069940.97, 1699.00, 1699.00, 1.20) GC UCART1
ALL HIGH 25TH HIGH VALUE IS	599.79350 ON 12071904: AT (	766001.02, 7069990.97, 1699.20, 1699.20, 1.20) GC UCART1

*** RECEPTOR TYPES: GC = GRIDCART
 GP = GRIDPOLR
 DC = DISCCART

DP = DISCPOLR

*** AERMOD - VERSION 14134 ***
*** AERMET - VERSION 14134 ***

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**MODELOPTs: RegDFAULT CONC ELEV FLGPOL VectorWS

*** THE SUMMARY OF HIGHEST 24-HR RESULTS ***

** CONC OF PM_10 IN MICROGRAMS/M**3 **

GROUP ID OF TYPE GRID-ID	DATE AVERAGE CONC (YYMMDDHH)	NETWORK RECEPTOR (XR, YR, ZELEV, ZHILL, ZFLAG)
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ALL HIGH 1ST HIGH VALUE IS 306.47702c ON 12082724: AT ( 765451.02, 7069990.97, 1699.00, 1699.00,
1.20) GC UCART1
HIGH 2ND HIGH VALUE IS 243.35947 ON 12071924: AT ( 765951.02, 7070040.97, 1699.00, 1699.00, 1.20)
GC UCART1
HIGH 3RD HIGH VALUE IS 229.34289c ON 12080224: AT ( 765801.02, 7070040.97, 1699.00, 1699.00,
1.20) GC UCART1
HIGH 4TH HIGH VALUE IS 219.44021c ON 12082824: AT ( 765801.02, 7070040.97, 1699.00, 1699.00,
1.20) GC UCART1
HIGH 5TH HIGH VALUE IS 201.14505 ON 12082024: AT ( 765951.02, 7070040.97, 1699.00, 1699.00, 1.20)
GC UCART1
HIGH 6TH HIGH VALUE IS 194.99651 ON 12060624: AT ( 765951.02, 7070040.97, 1699.00, 1699.00, 1.20)
GC UCART1
HIGH 7TH HIGH VALUE IS 192.54988 ON 12082924: AT ( 765951.02, 7070040.97, 1699.00, 1699.00, 1.20)
GC UCART1
HIGH 8TH HIGH VALUE IS 186.00855 ON 12081024: AT ( 765951.02, 7070040.97, 1699.00, 1699.00, 1.20)
GC UCART1
HIGH 9TH HIGH VALUE IS 180.99018 ON 12071024: AT ( 766001.02, 7069990.97, 1699.20, 1699.20, 1.20)
GC UCART1
HIGH 10TH HIGH VALUE IS 178.79525c ON 12082724: AT ( 765901.02, 7069990.97, 1699.00, 1699.00,
1.20) GC UCART1
HIGH 25TH HIGH VALUE IS 146.46307 ON 12082224: AT ( 765851.02, 7070040.97, 1699.00, 1699.00,
1.20) GC UCART1

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*** RECEPTOR TYPES: GC = GRIDCART
GP = GRIDPOLR
DC = DISCCART
DP = DISCPOLR

*** AERMOD - VERSION 14134 ***
*** AERMET - VERSION 14134 ***

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**MODELOPTs: RegDFAULT CONC ELEV FLGPOL VectorWS

*** Message Summary : AERMOD Model Execution ***

----- Summary of Total Messages -----

```

A Total of 0 Fatal Error Message(s)
A Total of 1 Warning Message(s)
A Total of 64 Informational Message(s)

A Total of 8784 Hours Were Processed

A Total of 64 Calm Hours Identified

A Total of 0 Missing Hours Identified ( 0.00 Percent)

```

***** FATAL ERROR MESSAGES *****
*** NONE ***

***** WARNING MESSAGES *****
CO W116 21 MODOPT: Vector Wind Speeds specified on MODELOPT Keyword VECTORWS

APPENDIX D.

AERMOD OUTPUT SUMMARY FILE – CHAPTER 3, MODEL RUN 4

*** AERMOD - VERSION 14134 ***

*** AERMET - VERSION 14134 ***

PAGE 1

**MODELOPTs: NonDEFAULT CONC ELEV FLGPOL BETA LW2 VectorWS

*** MODEL SETUP OPTIONS SUMMARY ***

**Model Is Setup For Calculation of Average CONCentration Values.

-- DEPOSITION LOGIC --

**NO GAS DEPOSITION Data Provided.

**NO PARTICLE DEPOSITION Data Provided.

**Model Uses NO DRY DEPLETION. DRYDPLT = F

**Model Uses NO WET DEPLETION. WETDPLT = F

**Model Uses URBAN Dispersion Algorithm for the SBL for 833 Source(s),
for Total of 1 Urban Area(s):

Urban Population = 6000.0 ; Urban Roughness Length = 1.000 m

**Model Allows User-Specified Options:

1. Stack-tip Downwash.
2. Model Accounts for ELEVated Terrain Effects.
3. Use Calms Processing Routine.
4. Use Missing Data Processing Routine.
5. No Exponential Decay.
6. Urban Roughness Length of 1.0 Meter Used.

**Other Options Specified:

LOWWIND2 - Use LowWind2 BETA option

VECTORWS - User specifies that input wind speeds are VECTOR means

CCVR_Sub - Meteorological data includes CCVR substitutions

TEMP_Sub - Meteorological data includes TEMP substitutions

**Model Accepts FLAGPOLE Receptor Heights.

**The User Specified a Pollutant Type of: PM_10

**Model Calculates 2 Short Term Average(s) of: 1-HR 24-HR

**This Run Includes: 833 Source(s); 1 Source Group(s); and 2503 Receptor(s)

**Model Set To Continue RUNning After the Setup Testing.

**The AERMET Input Meteorological Data Version Date: 14134

**Output Options Selected:

Model Outputs Tables of Highest Short Term Values by Receptor (RECTABLE Keyword)

Model Outputs Tables of Overall Maximum Short Term Values (MAXTABLE Keyword)

Model Outputs Tables of Concurrent Short Term Values by Receptor for Each Day Processed (DAYTABLE Keyword)

Model Outputs External File(s) of Threshold Violations (MAXIFILE Keyword)

Model Outputs External File(s) of High Values for Plotting (PLOTFILE Keyword)

Model Outputs External File(s) of Values by Season and Hour-of-Day (SEASONHR Keyword)

Model Outputs External File(s) of Ranked Values (RANKFILE Keyword)

Model Outputs Separate Summary File of High Ranked Values (SUMMFILE Keyword)

**NOTE: The Following Flags May Appear Following CONC Values: c for Calm Hours

12 01 01	1 08	62.5	0.427	1.026	0.005	509.	671.	-91.9	0.10	0.40	0.21	4.60	303.	10.0	292.8	2.0
12 01 01	1 09	100.4	0.437	1.357	0.005	734.	693.	-61.2	0.10	0.40	0.19	4.60	277.	10.0	294.2	2.0
12 01 01	1 10	131.4	0.484	1.629	0.005	970.	806.	-63.3	0.10	0.40	0.18	5.10	271.	10.0	296.6	2.0
12 01 01	1 11	151.8	0.576	1.841	0.005	1210.	1047.	-92.4	0.10	0.40	0.18	6.20	274.	10.0	296.1	2.0
12 01 01	1 12	160.8	0.537	1.991	0.005	1445.	948.	-70.9	0.10	0.40	0.18	5.70	256.	10.0	298.4	2.0
12 01 01	1 13	155.6	0.488	2.042	0.007	1612.	822.	-54.9	0.10	0.40	0.18	5.10	263.	10.0	297.9	2.0
12 01 01	1 14	137.9	0.485	1.996	0.007	1695.	811.	-60.7	0.10	0.40	0.18	5.10	269.	10.0	297.4	2.0
12 01 01	1 15	120.7	0.611	1.932	0.007	1758.	1144.	-138.6	0.10	0.40	0.18	6.70	262.	10.0	297.2	2.0
12 01 01	1 16	96.2	0.565	1.808	0.008	1808.	1024.	-137.9	0.10	0.40	0.19	6.20	244.	10.0	298.2	2.0
12 01 01	1 17	58.1	0.516	1.536	0.008	1835.	892.	-173.1	0.10	0.40	0.21	5.70	251.	10.0	297.4	2.0
12 01 01	1 18	28.6	0.415	1.215	0.008	1843.	651.	-183.7	0.10	0.40	0.28	4.60	237.	10.0	294.8	2.0
12 01 01	1 19	-20.2	0.379	-9.000	-9.000	-999.	561.	198.1	0.10	0.40	0.55	4.60	254.	10.0	293.8	2.0
12 01 01	1 20	-31.0	0.365	-9.000	-9.000	-999.	530.	115.9	0.10	0.40	1.00	4.60	277.	10.0	292.8	2.0
12 01 01	1 21	-31.8	0.364	-9.000	-9.000	-999.	528.	111.9	0.10	0.40	1.00	4.60	340.	10.0	291.9	2.0
12 01 01	1 22	-27.9	0.315	-9.000	-9.000	-999.	425.	82.1	0.10	0.40	1.00	4.10	112.	10.0	291.4	2.0
12 01 01	1 23	-28.1	0.314	-9.000	-9.000	-999.	423.	81.3	0.10	0.40	1.00	4.10	40.	10.0	289.2	2.0
12 01 01	1 24	-32.5	0.363	-9.000	-9.000	-999.	525.	108.6	0.10	0.40	1.00	4.60	30.	10.0	289.1	2.0

First hour of profile data

YR MO DY HR HEIGHT F WDIR WSPD AMB_TMP sigmaA sigmaW sigmaV
 12 01 01 01 10.0 1 51. 5.70 287.0 99.0 -99.00 -99.00

F indicates top of profile (=1) or below (=0)

*** AERMOD - VERSION 14134 ***

*** AERMET - VERSION 14134 ***

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**MODELOPTs: NonDEFAULT CONC ELEV FLGPOL BETA LW2 VectorWS

*** THE SUMMARY OF HIGHEST 1-HR RESULTS ***

** CONC OF PM₁₀ IN MICROGRAMS/M³ **

GROUP ID	DATE	AVERAGE CONC	(YYMMDDHH)	NETWORK
OF TYPE GRID-ID				RECEPTOR (XR, YR, ZELEV, ZHILL, ZFLAG)
ALL HIGH 1ST HIGH VALUE IS	6154.98198	ON 12061503:	AT (	765442.00, 7070334.00, 1704.00, 1704.00, 1.20) DC
HIGH 2ND HIGH VALUE IS	4663.03199	ON 12043020:	AT (	765442.00, 7070334.00, 1704.00, 1704.00, 1.20) DC
HIGH 3RD HIGH VALUE IS	4394.29449	ON 12060424:	AT (	765442.00, 7070334.00, 1704.00, 1704.00, 1.20) DC
HIGH 4TH HIGH VALUE IS	3620.76655	ON 12030507:	AT (	765470.00, 7070078.00, 1699.50, 1699.50, 1.20) DC
HIGH 5TH HIGH VALUE IS	3582.78617	ON 12043022:	AT (	765442.00, 7070334.00, 1704.00, 1704.00, 1.20) DC
HIGH 6TH HIGH VALUE IS	3133.06857	ON 12042801:	AT (	765442.00, 7070334.00, 1704.00, 1704.00, 1.20) DC
HIGH 7TH HIGH VALUE IS	3091.87242	ON 12070615:	AT (	765442.00, 7070334.00, 1704.00, 1704.00, 1.20) DC
HIGH 8TH HIGH VALUE IS	2568.32872	ON 12042207:	AT (	765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 9TH HIGH VALUE IS	2552.54499	ON 12040907:	AT (	765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 10TH HIGH VALUE IS	2493.69424	ON 12031703:	AT (	765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 25TH HIGH VALUE IS	2026.26533	ON 12031907:	AT (	765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1

*** RECEPTOR TYPES: GC = GRIDCART
 GP = GRIDPOLR

DC = DISCCART
DP = DISCPOLR

*** AERMOD - VERSION 14134 ***

*** AERMET - VERSION 14134 ***

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**MODELOPTs: NonDEFAULT CONC ELEV FLGPOL BETA LW2 VectorWS

*** THE SUMMARY OF HIGHEST 24-HR RESULTS ***

** CONC OF PM_10 IN MICROGRAMS/M**3 **

GROUP ID	DATE	NETWORK
OF TYPE GRID-ID	AVERAGE CONC (YYMMDDHH)	RECEPTOR (XR, YR, ZELEV, ZHILL, ZFLAG)

ALL HIGH 1ST HIGH VALUE IS 569.39656 ON 12052224: AT (765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 2ND HIGH VALUE IS 562.16018 ON 12082524: AT (765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 3RD HIGH VALUE IS 511.58529 ON 12080524: AT (765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 4TH HIGH VALUE IS 477.48359 ON 12042624: AT (765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 5TH HIGH VALUE IS 460.63735c ON 12072124: AT (765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 6TH HIGH VALUE IS 448.85597 ON 12092624: AT (765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 7TH HIGH VALUE IS 437.86011 ON 12081524: AT (765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 8TH HIGH VALUE IS 418.26785 ON 12110424: AT (765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 9TH HIGH VALUE IS 404.46689 ON 12031724: AT (765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 10TH HIGH VALUE IS 366.00989 ON 12031624: AT (765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1
HIGH 25TH HIGH VALUE IS 279.40326 ON 12112324: AT (765663.90, 7070568.04, 1708.50, 1708.50, 1.20) GC UCART1

*** RECEPTOR TYPES: GC = GRIDCART
GP = GRIDPOLR
DC = DISCCART
DP = DISCPOLR

*** AERMOD - VERSION 14134 ***

*** AERMET - VERSION 14134 *** *** Kwadela PM10 Baserun *** 19:05:28

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**MODELOPTs: NonDEFAULT CONC ELEV FLGPOL BETA LW2 VectorWS

*** Message Summary : AERMOD Model Execution ***

----- Summary of Total Messages -----

A Total of 0 Fatal Error Message(s)
A Total of 5 Warning Message(s)
A Total of 64 Informational Message(s)

A Total of 8784 Hours Were Processed

A Total of 64 Calm Hours Identified

A Total of 0 Missing Hours Identified (0.00 Percent)

***** FATAL ERROR MESSAGES *****
*** NONE ***

***** WARNING MESSAGES *****
CO W116 21 MODOPT: Vector Wind Speeds specified on MODELOPT Keyword VECTORWS
CO W122 21 MODOPT: LowWind2 Beta Option specified on MODELOPT Keyword Non-DEFAULT
CO W132 21 MODOPT: Minimum sigmav value (SVmin) for LowWind2 Beta Opt 0.3 m/s
CO W133 21 MODOPT: Maximum FRAN value (FRANmax) for LowWind2 Beta Opt 0.95
CO W320 23 URBOPT: Input Parameter May Be Out-of-Range for Parameter URB-POP

APPENDIX E.

AERMOD OUTPUT SUMMARY FILE – CHAPTER 4'S MODEL RUN

*** AERMOD - VERSION 15181

*** AERMET - VERSION 15181

PAGE 1

**MODELOPTs: NonDEFAULT CONC ELEV BETA RURAL ADJ_U*

*** MODEL SETUP OPTIONS SUMMARY ***

**Model Is Setup For Calculation of Average CONCentration Values.

-- DEPOSITION LOGIC --

**NO GAS DEPOSITION Data Provided.

**NO PARTICLE DEPOSITION Data Provided.

**Model Uses NO DRY DEPLETION. DRYDPLT = F

**Model Uses NO WET DEPLETION. WETDPLT = F

**Model Uses RURAL Dispersion Only.

**Model Allows User-Specified Options:

1. Stack-tip Downwash.
2. Model Accounts for ELEVated Terrain Effects.
3. Use Calms Processing Routine.
4. Use Missing Data Processing Routine.
5. No Exponential Decay.

**Other Options Specified:

ADJ_U* - Use ADJ_U* BETA option for SBL in AERMET

CCVR_Sub - Meteorological data includes CCVR substitutions

TEMP_Sub - Meteorological data includes TEMP substitutions

**Model Assumes No FLAGPOLE Receptor Heights.

**The User Specified a Pollutant Type of: PM_10

**Model Calculates 2 Short Term Average(s) of: 1-HR 24-HR
and Calculates PERIOD Averages

**This Run Includes: 609 Source(s); 5 Source Group(s); and 1 Receptor(s)

with: 607 POINT(s), including
0 POINTCAP(s) and 0 POINTHOR(s)
and: 0 VOLUME source(s)
and: 2 AREA type source(s)
and: 0 LINE source(s)
and: 0 OPENPIT source(s)

**Model Set To Continue RUNning After the Setup Testing.

**The AERMET Input Meteorological Data Version Date: 15181

**Output Options Selected:

Model Outputs Tables of PERIOD Averages by Receptor

Model Outputs Tables of Highest Short Term Values by Receptor (RECTABLE Keyword)

Model Outputs Tables of Concurrent Short Term Values by Receptor for Each Day Processed (DAYTABLE Keyword)

Model Outputs External File(s) of Threshold Violations (MAXIFILE Keyword)

Model Outputs External File(s) of High Values for Plotting (PLOTFILE Keyword)

Model Outputs Separate Summary File of High Ranked Values (SUMMFILE Keyword)

**NOTE: The Following Flags May Appear Following CONC Values: c for Calm Hours
m for Missing Hours
b for Both Calm and Missing Hours

**Misc. Inputs: Base Elev. for Pot. Temp. Profile (m MSL) = 10.00 ; Decay Coef. = 0.000 ; Rot. Angle = 0.0
Emission Units = GRAMS/SEC ; Emission Rate Unit Factor = 0.10000E+07
Output Units = MICROGRAMS/M**3

**Approximate Storage Requirements of Model = 3.8 MB of RAM.

**Detailed Error/Message File: Chp4_Car.Rec.err
**File for Summary of Results: Chp4_Car.Rec.sum

*** AERMOD - VERSION 15181 *** C:\Lakes\AERMOD View\Chp4_Car.Rec\Chp4_Car.Rec.isc ***
10/26/16
*** AERMET - VERSION 15181 *** *** 23:07:11

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**MODELOPTs: NonDEFAULT CONC ELEV BETA RURAL ADJ_U*

*** METEOROLOGICAL DAYS SELECTED FOR PROCESSING ***
(1=YES; 0=NO)

```
1111111111 1111111111 1111111111 1111111111 1111111111
1111111111 1111111111 1111111111 1111111111 1111111111
1111111111 1111111111 1111111111 1111111111 1111111111
1111111111 1111111111 1111111111 1111111111 1111111111
1111111111 1111111111 1111111111 1111111111 1111111111
1111111111 1111111111 1111111111 1111111111 1111111111
1111111111 1111111111 1111111111 1111111111 1111111111
1111111111 1111111111 1111111111 1111111111 1111111111
1111111111 11111
```

METEOROLOGICAL DATA PROCESSED BETWEEN START DATE: 2013 7 1 1
AND END DATE: 2013 9 30 24

NOTE: METEOROLOGICAL DATA ACTUALLY PROCESSED WILL ALSO DEPEND ON WHAT IS INCLUDED IN THE DATA FILE.

*** UPPER BOUND OF FIRST THROUGH FIFTH WIND SPEED CATEGORIES ***
(METERS/SEC)

1.54, 3.09, 5.14, 8.23, 10.80,

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**MODELOPTs: NonDEFAULT CONC ELEV BETA RURAL ADJ_U*

*** UP TO THE FIRST 24 HOURS OF METEOROLOGICAL DATA ***

Surface file: ..\AERMET_Cpt4.SFC Met Version: 15181
Profile file: ..\AERMET_Cpt4.PFL
Surface format: FREE
Profile format: FREE
Surface station no.: 66666 Upper air station no.: 66666
Name: UNKNOWN Name: UNKNOWN
Year: 2013 Year: 2013

First 24 hours of scalar data

YR	MO	DY	JDY	HR	H0	U*	W*	DT/DZ	ZICNV	ZIMCH	M-O	LEN	Z0	BOWEN	ALBEDO	REF	WS	WD	HT
REF	TA	HT																	
13	07	01	182	01	-9.9	0.146	-9.000	-9.000	-999.	133.	23.4	0.05	1.00	1.00	2.10	288.	10.0	280.4	2.0
13	07	01	182	02	-9.9	0.146	-9.000	-9.000	-999.	133.	23.4	0.05	1.00	1.00	2.10	295.	10.0	280.4	2.0
13	07	01	182	03	-9.9	0.146	-9.000	-9.000	-999.	133.	23.4	0.05	1.00	1.00	2.10	294.	10.0	280.0	2.0
13	07	01	182	04	-15.5	0.183	-9.000	-9.000	-999.	188.	36.9	0.05	1.00	1.00	2.60	288.	10.0	279.6	2.0
13	07	01	182	05	-15.5	0.183	-9.000	-9.000	-999.	188.	36.9	0.05	1.00	1.00	2.60	301.	10.0	279.2	2.0
13	07	01	182	06	-15.4	0.183	-9.000	-9.000	-999.	188.	36.9	0.05	1.00	1.00	2.60	300.	10.0	280.0	2.0
13	07	01	182	07	-18.5	0.221	-9.000	-9.000	-999.	249.	53.6	0.05	1.00	1.00	3.10	302.	10.0	280.9	2.0
13	07	01	182	08	-12.2	0.261	-9.000	-9.000	-999.	320.	109.5	0.05	1.00	0.47	3.60	304.	10.0	281.6	2.0
13	07	01	182	09	43.5	0.299	0.849	0.005	423.	392.	-46.2	0.05	1.00	0.28	3.60	304.	10.0	285.1	2.0
13	07	01	182	10	98.7	0.349	1.308	0.005	682.	494.	-32.3	0.05	1.00	0.22	4.10	303.	10.0	288.8	2.0
13	07	01	182	11	138.0	0.356	1.595	0.005	885.	510.	-24.7	0.05	1.00	0.20	4.10	298.	10.0	292.2	2.0
13	07	01	182	12	158.4	0.395	1.868	0.005	1239.	594.	-29.1	0.05	1.00	0.19	4.60	291.	10.0	293.5	2.0
13	07	01	182	13	160.2	0.395	1.927	0.005	1343.	595.	-28.8	0.05	1.00	0.19	4.60	292.	10.0	294.9	2.0
13	07	01	182	14	143.3	0.392	1.900	0.005	1438.	589.	-31.6	0.05	1.00	0.20	4.60	290.	10.0	296.1	2.0
13	07	01	182	15	106.5	0.351	1.747	0.005	1504.	499.	-30.3	0.05	1.00	0.21	4.10	291.	10.0	294.2	2.0
13	07	01	182	16	53.4	0.268	1.397	0.005	1534.	336.	-26.9	0.05	1.00	0.27	3.10	301.	10.0	292.4	2.0
13	07	01	182	17	-3.6	0.151	-9.000	-9.000	-999.	148.	71.6	0.05	1.00	0.44	2.10	314.	10.0	290.5	2.0
13	07	01	182	18	-15.0	0.183	-9.000	-9.000	-999.	189.	37.0	0.05	1.00	1.00	2.60	333.	10.0	288.1	2.0
13	07	01	182	19	-15.1	0.183	-9.000	-9.000	-999.	188.	37.0	0.05	1.00	1.00	2.60	338.	10.0	285.8	2.0
13	07	01	182	20	-18.4	0.221	-9.000	-9.000	-999.	249.	53.6	0.05	1.00	1.00	3.10	355.	10.0	283.4	2.0
13	07	01	182	21	-18.4	0.221	-9.000	-9.000	-999.	249.	53.6	0.05	1.00	1.00	3.10	340.	10.0	282.6	2.0
13	07	01	182	22	-15.3	0.183	-9.000	-9.000	-999.	189.	37.0	0.05	1.00	1.00	2.60	345.	10.0	281.9	2.0
13	07	01	182	23	-15.4	0.183	-9.000	-9.000	-999.	188.	36.9	0.05	1.00	1.00	2.60	343.	10.0	281.2	2.0
13	07	01	182	24	-15.4	0.183	-9.000	-9.000	-999.	188.	36.9	0.05	1.00	1.00	2.60	344.	10.0	280.9	2.0

First hour of profile data

YR MO DY HR HEIGHT F WDIR WSPD AMB_TMP sigmaA sigmaW sigmaV
 13 07 01 01 10.0 1 288. 2.10 280.4 99.0 -99.00 -99.00

F indicates top of profile (=1) or below (=0)

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**MODELOPTs: NonDEFAULT CONC ELEV BETA RURAL ADJ_U*

*** THE SUMMARY OF MAXIMUM PERIOD (2208 HRS) RESULTS ***

** CONC OF PM_10 IN MICROGRAMS/M**3 **

NETWORK
 GROUP ID AVERAGE CONC RECEPTOR (XR, YR, ZELEV, ZHILL, ZFLAG) OF TYPE GRID-
 ID

 POINTSQU 1ST HIGHEST VALUE IS 16.17724 AT (76555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC
 2ND HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 3RD HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 4TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 5TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 6TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 7TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 8TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 9TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 10TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)

WASTEBUR 1ST HIGHEST VALUE IS 0.00314 AT (76555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC
 2ND HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 3RD HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 4TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)

5TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 6TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 7TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 8TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 9TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 10TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)

INDUSTRI 1ST HIGHEST VALUE IS 0.08383 AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC
 2ND HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 3RD HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 4TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 5TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 6TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 7TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 8TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 9TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 10TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)

DUST 1ST HIGHEST VALUE IS 28.03274 AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC
 2ND HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 3RD HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 4TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 5TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 6TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 7TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 8TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 9TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 10TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)

*** AERMOD - VERSION 15181 *** ** C:\Lakes\AERMOD View\Chp4_Car.Rec\Chp4_Car.Rec.isc ***
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**MODELOPTs: NonDEFAULT CONC ELEV BETA RURAL ADJ_U*

*** THE SUMMARY OF MAXIMUM PERIOD (2208 HRS) RESULTS ***

** CONC OF PM_10 IN MICROGRAMS/M**3 **

NETWORK
 GROUP ID AVERAGE CONC RECEPTOR (XR, YR, ZELEV, ZHILL, ZFLAG) OF TYPE GRID-
 ID

 ALL 1ST HIGHEST VALUE IS 44.29694 AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC
 2ND HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 3RD HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 4TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 5TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 6TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 7TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 8TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 9TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)
 10TH HIGHEST VALUE IS 0.00000 AT (0.00, 0.00, 0.00, 0.00, 0.00)

*** RECEPTOR TYPES: GC = GRIDCART
 GP = GRIDPOLR
 DC = DISCCART
 DP = DISCPOLR

*** AERMOD - VERSION 15181 *** ** C:\Lakes\AERMOD View\Chp4_Car.Rec\Chp4_Car.Rec.isc ***
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 *** AERMET - VERSION 15181 *** ** *** 23:07:11

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**MODELOPTs: NonDEFAULT CONC ELEV BETA RURAL ADJ_U*

*** THE SUMMARY OF HIGHEST 1-HR RESULTS ***

** CONC OF PM_10 IN MICROGRAMS/M**3 **

GROUP ID OF TYPE GRID-ID	DATE AVERAGE CONC (YYMMDDHH)	NETWORK RECEPTOR (XR, YR, ZELEV, ZHILL, ZFLAG)
-----------------------------	---------------------------------	---

POINTSOU HIGH 1ST HIGH VALUE IS 114.20172 ON 13081008: AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC

WASTEBUR HIGH 1ST HIGH VALUE IS 0.01893 ON 13073008: AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC

INDUSTRI HIGH 1ST HIGH VALUE IS 2.96405 ON 13070712: AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC

DUST HIGH 1ST HIGH VALUE IS 162.18545 ON 13073008: AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC

ALL HIGH 1ST HIGH VALUE IS 269.93791 ON 13071217: AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC

*** RECEPTOR TYPES: GC = GRIDCART
 GP = GRIDPOLR
 DC = DISCCART
 DP = DISCPOLR

*** AERMOD - VERSION 15181 *** ** C:\Lakes\AERMOD View\Chp4_Car.Rec\Chp4_Car.Rec.isc ***
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**MODELOPTs: NonDEFAULT CONC ELEV BETA RURAL ADJ_U*

*** THE SUMMARY OF HIGHEST 24-HR RESULTS ***

** CONC OF PM_10 IN MICROGRAMS/M**3 **

GROUP ID OF TYPE GRID-ID	DATE AVERAGE CONC (YYMMDDHH)	NETWORK RECEPTOR (XR, YR, ZELEV, ZHILL, ZFLAG)
-----------------------------	---------------------------------	---

POINTSOU HIGH 1ST HIGH VALUE IS 49.80435c ON 13081024: AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC

WASTEBUR HIGH 1ST HIGH VALUE IS 0.00716c ON 13081024: AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC

INDUSTRI HIGH 1ST HIGH VALUE IS 0.63289c ON 13090524: AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC

DUST HIGH 1ST HIGH VALUE IS 70.89136c ON 13081024: AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC

ALL HIGH 1ST HIGH VALUE IS 120.80281c ON 13081024: AT (765555.00, 7070258.00, 1719.14, 1719.14, 0.00) DC

*** RECEPTOR TYPES: GC = GRIDCART
 GP = GRIDPOLR

DC = DISCCART
DP = DISCPOLR

*** AERMOD - VERSION 15181 *** *** C:\Lakes\AERMOD View\Chp4_Car.Rec\Chp4_Car.Rec.isc ***

10/26/16

*** AERMET - VERSION 15181 *** ***

*** 23:07:11

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**MODELOPTs: NonDEFAULT CONC ELEV BETA RURAL ADJ_U*

*** Message Summary : AERMOD Model Execution ***

----- Summary of Total Messages -----

A Total of 0 Fatal Error Message(s)
A Total of 1 Warning Message(s)
A Total of 29 Informational Message(s)

A Total of 2208 Hours Were Processed

A Total of 29 Calm Hours Identified

A Total of 0 Missing Hours Identified (0.00 Percent)

***** FATAL ERROR MESSAGES *****

*** NONE ***

***** WARNING MESSAGES *****

ME W187 1945 MEOpen: ADJ_U* Beta Option for Low Winds used in AERMET Non-DEFAULT