The health and economic benefits of interventions to reduce residential solid fuel burning on the Highveld

LF Lindeque

orcid.org 0000-0002-2221-8225

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

Supervisor: Dr RP Burger

Co-supervisor: Prof SJ Piketh

Graduation May 2018

2390420

DEDICATION

I dedicate this work to my mother, Dr Koba van der Walt, who lost her battle with Leukaemia during the course of this study on 31 August, 2016.

She dedicated a large part of her life to the promotion and protection of public health in the Vaal Triangle and provided me with valuable insights and advice. Without her love and support (and toasted sandwiches during late night study sessions) I would not have been able to continue my post-graduate studies. Her compassion for people and passion for justice continues to inspire me to make a difference in the world.

I am honoured to be your daughter and hope that I can one day be half the woman you were.

You are sorely missed.

PREFACE

The article model adopted by the Faculty of Natural Sciences in terms of the General Rules of the North-West University (NWU) was followed for the submission of the research component of this post-graduate study. The work presented in this dissertation was conducted by the author between January 2016 and November 2017 and contains original data that has never been published or previously submitted for degree purposes to any university.

The author was personally involved in the conceptualization, collection and analysis of all data as well as the writing of the manuscripts and dissertation document. Where use was made of work by other researchers, such work is duly acknowledged in the text.

The overarching format and reference style of this dissertation is in accordance with the specifications provided in the Manual for Post-graduate students of the NWU. The referencing style and format of each manuscript differ slightly however, as they have been prepared in accordance with the unique requirements of the journals/conferences to which they have been submitted/will be submitted to.

The dissertation document includes three manuscripts, two of which have been peer reviewed and accepted for publication. Each manuscript is included as a chapter of the dissertation. Details of the manuscripts are as follows:

Manuscript 1 (Chapter 3):

Lindeque, L.F., Burger, R.P. & Piketh, S.J. 2016. Health impact assessment of interventions to reduce solid fuel burning: challenges and considerations. In: *National Association for Clean Air*. ISBN: 978-0-620-70646-9, Mbombela, South Africa, 10-13 October 2016.

This paper was presented at the National Association for Clean Air Conference held in Mbombela, South Africa, 10-13 October ,2016. The paper was peer reviewed and published in the conference proceedings (ISBN: 978-0-620-70646-9).

Guidelines for authors can be accessed by following this link to the National Association for Clean Air Website.

The paper addresses the first Objective of this study: *to investigate and evaluate the relevant socio-economic and physical variables needed to conduct the health and economic benefit assessment in the South African context.*

Consent from co-authors is attached as an Annexure.

Manuscript 2 (Chapter 4):

Lindeque, L.F., Burger, R.P. & Piketh, S.J. 2016. The health and economic benefits of thermal insulation interventions to improve air quality in a South African township. *Aerosol and Air Quality Research*.

This paper was submitted to the *International journal of Aerosol and Air Quality Research.* It was accepted for publication with minor revisions. Revisions have been made, submitted and are currently under review.

According to the copyright agreement of the journal, an author retains the right: "to use the article or any part thereof free of charge in a printed compilation of works of their own, such as collected writings or lecture notes, in a thesis, or to expand the article into book-length form for publication". Thus, no copyright permission is needed to include this paper in the dissertation document.

Guidelines for authors and information regarding copyrights can be accessed by following this link to the AAQR journal website.

The paper addresses the first Objective of this study: *To investigate and evaluate the relevant socio-economic and physical variables needed to conduct the health and economic benefit assessment in the South African context* and part of Objective 2: *To quantify the spatial variation of pre- and post-intervention PM concentrations over the Highveld.*

Consent from co-authors is attached as an Annexure*.*

Manuscript 3 (Chapter 5):

Lindeque, L.F., Burger, R.P., & Piketh, S.J., 2017. The health and economic benefits of thermal insulation as air quality intervention on the Highveld.

This manuscript has not yet been submitted to a journal. The Clean Air Journal is being considered as a suitable journal for submission, and thus the manuscript is formatted in accordance with the requirements of this journal.

Guidelines for authors and details about the journal can be accessed by following this link to the Clean Air Journal website.

The paper addresses the third Objective of the study: *Determine the size and spatial distribution of health and economic benefits associated with reduced residential solid fuel burning in low-income settlements on the Highveld*

Consent from co-authors is attached as an Annexure.

Dissertation outline

Chapter 1 provides the background and motivation for this research. It includes the scope, aims and objectives of this study and contains a review of relevant literature consulted. As each manuscript also contains a literature review section, reference is made to relevant sections in each manuscript to avoid repetition where appropriate.

Chapter 2 provides an overview of the data and methods used to achieve the aim and objectives set out in Chapter 1. Once again, reference is made to relevant sections in the respective manuscripts where data and methods for each objective are described in detail.

In Chapter 3, the relevant socio-economic and physical variables needed to conduct health and economic impact assessments are investigated and evaluated.

In Chapter 4, the community scale intervention and methods used to calculate post-intervention $PM_{2.5}$ concentrations used in the regional scale health impact assessment are discussed in detail.

In Chapter 5, these results are then used to quantify the spatial variation of pre-and post-intervention $PM_{2.5}$ concentrations over the Highveld. Steps followed to conduct the health impact assessment and economic valuation is then described, followed by a description of the size and spatial distribution of the health and economic benefits associated with reduced residential solid fuel burning in low-income settlements in the study area.

Chapter 6 summarises the major findings and results of the study.

ABSTRACT

Due to its complicated history, South Africa faces air quality problems associated with both developed and developing countries. On the one hand, industrial activities and high numbers of private vehicle ownership are significant sources of emissions, whilst on the other, solid fuel burning by large numbers of the population and a strong agricultural sector also contribute significantly to air quality problems. This complex mix of sources pose a challenge for air quality management (AQM) in South Africa.

The legacy of apartheid policies that created extreme inequality and inequity for over four decades still affects all aspects of South African society, including public health. The environments and quality of housing where people live is one of the strongest determinants of public health. Despite efforts by government, many residents of low-income settlements are still living in conditions of extreme poverty, with less access to quality basic services like healthcare, sanitation, electricity and education. These households often cannot afford to use electricity as their only energy source and supplement their energy needs by burning solid fuels for cooking and/or heating purposes. Low socio-economic status also increases vulnerability to the adverse health impacts of air pollution. In many parts of the developing world, including South Africa, residential solid fuel burning is widespread enough to contribute significantly to ambient air pollution levels and can have impacts on health far from the original source.

The Department of Environmental Affairs' recently published air quality offset guidelines mention residential solid fuel burning as a source that could be addressed in offset programmes. Several community scale pilot offset programmes have been implemented in densely populated low-income areas on the Highveld, but quantifying their true impact remains a challenge. More information is needed in order to identify the most suitable interventions for large-scale roll-out in the area. A need thus exists to quantify the impact of individual pilot offset projects on a larger scale. Health impact Assessment (HIA) could be a useful tool to quantify the health and associated economic benefits of air pollution interventions and provide a more comprehensive understanding of their true impact.

This study takes a predictive approach, as it aims to assess the future health impact of a specific intervention measure. This approach required making assumptions about future trends involving the study population, health outcomes, the time required to achieve decrease pollutant levels as well when health outcomes will occur. These assumptions introduce uncertainties in any HIA.

 Air quality data from monitoring stations in the study area were used to quantify the spatial variation of average annual $PM_{2.5}$ concentrations by using the enumeration area (EA) dataset of the 2011 census. This scale of analysis was chosen to better represent the high spatial variability of factors

that influence pollution concentrations and exposure to household emissions in densely populated low-income communities.

In order to most accurately represent the context of this study, the findings from a pilot air quality offset programme implemented at the community scale was used as the control scenario. To create the post-intervention air quality dataset, the control value (a 4 μgm^3 reduction in mean $PM_{2.5}$) was applied to EAs where more than 10% of households reported using dirty fuels as an energy source and the HIA was conducted in only these identified communities. This approach was aimed at reducing uncertainty by using spatially refined estimates of site specific air quality, population and mortality data for each EA. The economic value of avoided mortality estimates was calculated by applying the value of a statistical life calculated for South Africa as valuation measure. Results were aggregated at the local municipality level for easier reporting. Our analysis estimated that the modelled improvements in air quality over the Highveld could avoid 143 premature mortalities over 20 years, with an associated economic benefit of ZAR (2011) 371.4 million.

Even though existing models use significant assumptions to link air quality with health outcomes, these results could provide valuable insight into the true impact of improved air quality in low-income settlements on the Highveld. Attaching a monetary value to improved health outcomes could further inform decision making regarding the suitability of this offset for the private sector and government alike, despite the limitations involved in the calculation of cost estimates.

Keywords: Air quality offsets, air pollution interventions, economic valuation, economic benefits, Health Impact Assessment, residential solid fuel use

ACKNOWLEDGEMENTS

GLOSSARY

AAP	Ambient Air Pollution
AEL	Air Emission Licence
APPA	Air Pollution Prevention Act
AQM	Air quality management
BenMAP	Environmental Benefits and Analysis Mapping Program
CBA	Cost-benefit analysis
CBD	Central business district
CEA	Cost-effectiveness analysis
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPI	Consumer Price Index: An economic conversion factor that measures changes in price levels over time within a country
CRF	Concentration Response Function
CUA	Cost-utility analysis
DEA	Department of Environmental Affairs
DEAT	Department of Environmental Affairs and Tourism
FRIDGE	Fund for Research into Industrial Development Growth and Equity

GBD	Global Burden of Disease
H$_2$S	Sulphuric Acid
HAP	Household Air Pollution
HIA	Health Impact Assessment
HNO$_3$	Nitric Acid
HPA	Highveld Priority Area
IAP	Indoor Air Pollution
IPWM	Integrated Policy for Pollution and Waste Management
NAAQS	National Ambient Air Quality Standards
NEMA	National Environmental Management Act
NEMAQA	National Environmental Management: Air Quality Act
NO	Nitrogen Oxide
NO$_2$	Nitrogen Dioxide
OECD	Organisation for Economic Co-operation and Development
PM	Particulate Matter
PPP	Purchasing Power Parity**:** An economic conversion factor used to measure changes in price levels across countries, or regions within a country
SAAQIS	South African Air Quality Information System
STASSA	Statistics South Africa

U.S. EPA	United States Environmental Protection Agency
UFP	Ultra-Fine Particles
VOCs	Volatile Organic Compounds
VSL	Value of a statistical life
VTAPA	Vaal Triangle Airshed Priority Area
WBPA	Waterberg-Bonjala Priority Area
WHO	World Health Organization
ZAR	South African Rand

TABLE OF CONTENTS

xiv

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1   Background and motivation for the study

The South African Highveld is an area well known for its poor air quality. Due to rich coal reserves in the area, many coal-fired power plants and heavy industries are located here. The area is also densely populated, resulting in large-scale exposure to pollutants that are harmful to human health. The existing air poor air quality and potential for further deterioration has led to the declaration of two priority air quality management areas, the Vaal Triangle Air Shed Priority Area (VTAPA) and Highveld Priority Area (HPA), in terms of Chapter 4 of the National Environmental Management: Air Quality Act no.39 of 2004 South Africa, 2004).

Although overall emissions from industrial, mining and other commercial sources are mostly higher than those attributable to household combustion in both priority areas, the impact of the latter on human health is of far bigger significance (Ezzati & Kammen, 2002). Smoke from solid fuel and coal burning contain a large number of pollutants known to be hazardous to human health and are emitted at much lower levels, where human exposure is at its highest and pollutant dispersal is limited. Living in areas with high air pollution levels has been linked with increased risk of respiratory, cardio- and cerebrovascular morbidity and mortality, all cause mortality,as well as acute effects like skin and eye irritation (Pope & Dockery, 2006; Brook *et al.*, 2010; WHO, 2013).

The negative health impacts of air pollution place a significant economic burden on affected individuals, their families, the public healthcare system and the economy of a country. These costs include the costs associated with illness or premature death and loss of productivity due to illness. Global air pollution related health costs were estimated to be US$ 21 billion in 2015 and are expected to increase to US$ 176 billion in 2060 (OECD,2016).

Interventions aimed at reducing residential solid fuel burning in exposed communities have the potential to reduce air pollution, population exposure and associated negative health impacts and economic costs (FRIDGE 2004). Successful interventions should reduce the environmental, social and economic impacts of poor air quality to be truly sustainable, but their success is often considered in terms of air quality measurements only. Measuring air quality alone does not shed any light on the socio-economic benefits of an intervention measure and this often results in

interventions being classified as unsustainable and not cost effective (Wright & Oosthuizen, 2002).

The recently published air quality offset guidelines (DEA, 2016), mention residential solid fuel burning as a source that could be addressed in offset programs. The guidelines clearly state that an offset should counterbalance the environmental impacts of a pollutant from one source by decreasing emissions from another source that has an equivalent impact (Garland *et al.*, 2016). Several pilot offset programmes have been implemented in densely populated low-income areas on the Highveld, but quantifying their true impact remains a challenge. There seems to be consensus however, that the health impacts of interventions should be quantified and used as a measure of their effectiveness and suitability for large-scale roll-out. Interventions (and pilot offset programmes) are typically tested and implemented at the community scale to determine suitability for larger scale roll-out. Previous studies of various intervention methods revealed no significant improvements in overall ambient air quality (Von Schirnding et al. 2002; FRIDGE 2004; Van Niekerk 2006). These small changes in air quality at the community level only provide marginal changes in health risk for the exposed population, but the sum of the same reductions in a larger population and at a larger scale could result in significant health and economic benefits (Pope and Dockery, 2006; U.S. EPA, 2012).

A need thus exists to model the impact of individual pilot offset projects on a larger scale. This could provide a much clearer picture of their true impact and will better inform decision making and the allocation of resources. Health impact Assessment (HIA) could be a useful tool to quantify the health and economic benefits of air pollution interventions, but current methodologies contain limitations, and assumptions must be made that can introduce uncertainty into results. Assessing the success of interventions based on findings made in only one area, community or population could lead to the wrong conclusions being made due to many confounding and interactive factors that vary over time, space and populations (Von Schirnding et al. 2002; Finkelstein et al. 2005). Using site specific air quality, population and health data to model the impact of an intervention over the regional scale could provide a better estimate of its true impact.

This study will aim to fill this gap by estimating the impact that the large-scale implementation of thermal insulation as an air pollution intervention measure will have on the air quality and population health in densely populated low-income settlements on the Highveld. The health benefits (in terms of reduced premature mortality) and the economic value of these benefits are calculated in order to quantify the health and economic impacts that an offset aimed at reducing residential solid fuel burning could have if implemented on the regional scale. Even though existing models use significant assumptions to link air quality with health outcomes, these results

could provide valuable insight into the true impact of improved air quality in low-income settlements on the Highveld. Attaching a monetary value to improved health outcomes could further inform decision making regarding the suitability of this offset for the private sector and government alike, despite the limitations involved in the calculation of cost estimates.

1.2 Scope of the study

This study aims to assess the impact of a specific intervention (thermal insulation) on air quality population exposure and health from a specific source (residential solid fuel burning) on the Highveld. As such, the focus of this research is on the drivers and impacts of emissions from residential solid fuel burning in low income settlements specifically.

Careful consideration was given to select the pollutant and health outcome for the analysis. Based on current evidence, long-term exposure to fine particulate matter, <2.5 µm in aerodynamic diameter ($PM_{2.5}$), poses the most significant threat to human health by increasing risk of cardiovascular-, cerebrovascular- and respiratory morbidity and mortality in exposed populations (Pope & Dockery, 2006; Brook *et al.*, 2010). No reliable morbidity data were available for the study area and thus the focus of this study is on the most severe health outcome, premature mortality. Although brief discussions about other sources, pollutants and health outcomes are included in this work, the vast majority of topics discussed focus on $PM_{2.5}$, residential solid fuel burning and their impact on mortality over the long-term.

The health impact assessment was only conducted in areas where residents reported using solid fuels to supplement their energy needs, to better estimate the impact of reducing source specific emissions on the exposed population. A large part of the population residing in the study area was thus not included in the health impact assessment, as they are unlikely to be exposed to the high concentrations often found in densely populated low-income settlements.

1.3 Aim and objectives

The aim of this study is to estimate the health and associated economic benefits of the large-scale implementation of thermal insulation in low-income settlements on the Highveld in order to inform decision making about the suitability of this measure as an option for future air quality offsetting.

To reach this aim, the following objectives were set:

1. Investigate and evaluate the relevant socio-economic and physical variables needed to conduct the health and economic impact assessment in the South African context.

2. Quantify the spatial variation of pre- and post- intervention PM2.5 concentrations over the Highveld.

3. Determine the size and spatial distribution of health and economic benefits associated with reduced residential solid fuel burning in low-income settlements on the Highveld.

1.4 Literature review

1.4.1 Air pollution

Air pollution can be defined as *"the presence of contaminants in air in sufficient quantities to impair human and animal health and welfare, vegetation and materials"* (Murray & McGranahan, 2003 *in* Matooane & Diab, 2011:1)*. Raghunandan, Matooane and Oosthuizen (2008:1) describe air pollution as *"the contamination of the air by harmful gases and particulates at concentrations that are higher than natural background levels"*. In the National Environmental Management: Air Quality Act (no.39 of 2004) it is classified as *"any change in the composition of the air caused by smoke, soot, dust (including fly ash), cinders, solid particles of any kind, gases, fumes, aerosols and odorous substances"* (DEA, 2004:20).

Air pollution can be of natural or anthropogenic origin. Natural sources of air pollution include geogenic emissions (e.g. wildfires, volcanic ash, sea salt and dust) and biogenic emissions for example, pollen and methane emissions from swamps (Daly & Zannetti, 2007). Pollution from anthropogenic sources can be attributed to activities like fossil fuel combustion, agricultural activities, vehicle emissions and industrial processes to name a few (Hutton, 2011). The following sections will provide a brief overview of air pollution in general and then focus more specifically on the aspects of greatest concern in the context of this study.

1.4.2 Primary and secondary pollutants

Regardless of their origin, pollutants are further classified as primary or secondary. Primary pollutants, also known as precursors, are emitted directly from their source into the atmosphere. Secondary pollutants form in the atmosphere from the precursor (primary) pollutants and are thus not directly emitted from a source (Daly & Zannetti, 2007).

Both primary and secondary pollutants can cause harm in high enough concentrations. The traditional wintertime London smog of the 20th century, including the infamous "great killer smog" of December 1952, was caused mainly by sulphur compounds emitted directly from coal burning. The presence of a temperature inversion caused by an extensive high-pressure system resulted in smoke, soot, fly ash and sulphur dioxide (all primary pollutants) being trapped close to the surface, forming a deadly smog (Daly & Zanetti, 2007; Brockington; 2017). Thousands were admitted to

hospitals and it is estimated that the smog resulted in approximately 12 000 deaths during the episode and the days, weeks and months that followed (Bell & Davis, 2001).

The formation of secondary pollutants is known to cause the "Los Angeles" smog, named after the city where it was first recognised. This smog is a product of photochemical reactions involving nitrogen oxides, VOCs and sunlight and produces ozone and other secondary chemicals. This tropospheric or low-level ozone can cause harm to plants and animals and eye irritation, exacerbation of respiratory diseases in humans. Other secondary pollutants like nitrates, sulphates and organic particles can be transported over very large distances where their deposition contribute to acid rain that can damage crops, vegetation, soil and contaminate bodies of water far away from their original source (Daly & Zannetti, 2007). Table 1-1 below provides a summary and examples of common primary and secondary air pollutants.

Table 1-1. Primary and Secondary Pollutants.

Primary Pollutants	Examples	Secondary Pollutants	Examples
Carbon Compounds	CO, CO_2, CH_4 and VOCs	NO_2 and HNO_3	Formed from NO
Nitrogen Compounds	NO, N_2O and NH_3	Ozone (O_3)	Formed from photochemical reactions of nitrogen oxides and VOCs
Sulphur compounds	H_2S and SO_2	Sulfuric and nitric acid droplets	Formed from SO_2 and NO_2
Halogen Compounds	E.g. Chlorides, fluorides and bromides	Sulphate and nitrate aerosols	Formed from reactions of sulfuric and nitric acid droplets
Particulate Matter (PM)	Aerosols in liquid or solid form	Organic aerosols	Formed from VOCs in gas to particle reactions

Source: Daly & Zanetti, 2007.

1.4.3   Indoor, ambient and household air pollution

Air pollution can occur both indoors and in the ambient environment and is most often classified as such in scientific literature and policy documents as they mostly involve different sources and vulnerable populations (Hutton *et al.*, 2007). In the comparative risk assessment of household solid fuel use conducted as part of the 2010 Global Burden of Disease (GBD) project, Smith *et al.* (2014) reframed the previously used risk factor "indoor air pollution form household use of solid fuel" as

they felt it inadequately described the extent of household emissions and the risks associated. The risk factor was reframed as "household air pollution from solid cook fuel" (HAP) to better indicate that the burden of disease is attributable to all forms of exposure to this source and not only to exposure occurring in one place in a household (Smith *et al*., 2014, StatsSA, 2017).

The rationale behind this reframing is as follows: Pollution from residential solid fuel burning does not only occur indoors, but also in the near household environment. In many parts of the developing world, including South Africa, residential solid fuel burning is widespread enough to contribute significantly to ambient air pollution (AAP) levels and can have impacts on health far from the original source. Cooking practices also vary greatly, and cooking with solid fuels can also occur outside the home. The term indoor air pollution further implies that a chimney or ventilation could eliminate the problem without truly addressing the root cause, incomplete combustion of dirty fuels. Solid fuels are also not exclusively used for cooking, but for heating and lighting purposes also. On the Highveld for example, more households report using solid fuels for heating than for cooking purposes. The broader term "household air pollution from solid cook fuel" more accurately represent all forms of exposure to this source (Smith *et al., 2014;* StatsSA,2017).

Main pollutants emitted through residential burning include particulate matter (PM) <10 μm in aerodynamic diameter (PM_{10}), fine particulates <2.5 μm in aerodynamic diameter ($PM_{2.5}$), ultrafine particles <0.1 μm in aerodynamic diameter (UFP), carbon monoxide, formaldehyde, Sulphur oxides and polycyclic organic matter. The strongest evidence for elevated mortality risk is associated with $PM_{2.5}$ and UFP exposure. Coarse particles and gaseous pollutants have been found to be associated mainly with short term irritant effects at typical ambient concentrations (Brook *et al*., 2010; Kan *et al*., 2007; WHO, 2006). Since PM is the pollutant of focus of this study, it is discussed in more detail below.

1.5   Particulate Matter

Particulate matter (PM) consists of a mixture of solid and/or liquid particles (organic and inorganic) suspended in air. Even though PM is a widespread pollutant, the chemical and physical characteristics of the PM mixture can vary greatly by location and source. The fact that PM can be formed primarily or secondarily and continues to undergo chemical and physical transformation whilst in the atmosphere, further adds to its complexity. This variability complicates the study of exposure and risks as different characteristics of PM may cause different health effects. (Samet *et al.,* 2006). There is currently not enough evidence at the population level to conclusively determine the effects of different chemical compositions or sources of PM on health (WHO, 2006).

Although more studies are focusing specifically on the health implications of specific chemical components of PM (Kelly & Fussell, 2012; Reiss *et al*., 2007; Stanek *et al*., 2011), air quality

guidelines still classify particles by their aerodynamic properties. This is still the most widely used method of classification because the aerodynamic properties of particulates influence their transport and removal from the atmosphere as well as their deposition sites and clearance pathways in the respiratory system (WHO, 2006).

The size of suspended particles in the atmosphere can vary from a few nano meters to tens of micro meters and are classified into four fractions. Total Suspended Particles (TSP) refer to the total mix of suspended particles in the air including large particles between <50 - 100 μm in aerodynamic diameter. The course fraction includes particles <10 μm in aerodynamic diameter (PM_{10}) and are also known as thoracic or inhalable particles. PM_{10} contains within it the coarse ($PM_{10-2.5}$) and fine ($PM_{2.5}$) fractions. Fine particulates <2.5 μm in aerodynamic diameter ($PM_{2.5}$) includes fine and ultrafine particles (UFP) <0.1 μm in aerodynamic diameter (GBD 2013 Risk Factors Collaborators, 2015; Pascal *et al*., 2011).

The coarse PM fraction mostly contains particles produced from the mechanical break up of larger particles such as suspended and re suspended dust from roads and industrial activities, wind-blown dust form agricultural activities, and biological materials like sea salt, pollen and bacterial fragments. The fine particle mix contains directly emitted combustion particles, re-condensed organic and metal vapours, and secondary particles formed from other gaseous pollutants present in the atmosphere (Samet *et al.,* 2006). Ultrafine particles are also emitted from combustion activities and formed through secondary atmospheric processes, but have a very short atmospheric life time (minutes to hours) as they rapidly coagulate and condensate to form larger ($PM_{2.5}$) particles (Pope & Dockery, 2006). Figure 1-1 shows the size range of airborne particles and the typical size range of some common components of PM.

Evidence from toxicological studies indicate that $PM_{2.5}$ may have the largest negative impact on human health, because the particle mix contains sulphates, metals, nitrates and other particles with harmful chemicals absorbed onto their surfaces. Furthermore, $PM_{2.5}$ remains suspended in the atmosphere longer than other particles, are transported over longer distances and penetrate indoor environments more regularly than larger particles (Pope & Dockery, 2006).

The fact that PM is such a pervasive pollutant known to be harmful to human health has resulted in the establishment of standards and guidelines for acceptable ambient concentrations of both PM_{10} and $PM_{2.5}$ worldwide, including South Africa. PM emissions from residential solid fuel burning is however a difficult source to manage and has only fairly recently been included in air quality management plans when the approach to air quality management changed in the country. The following section will provide a brief history of air quality management in South Africa, followed by a discussion of current legislation and management tools.
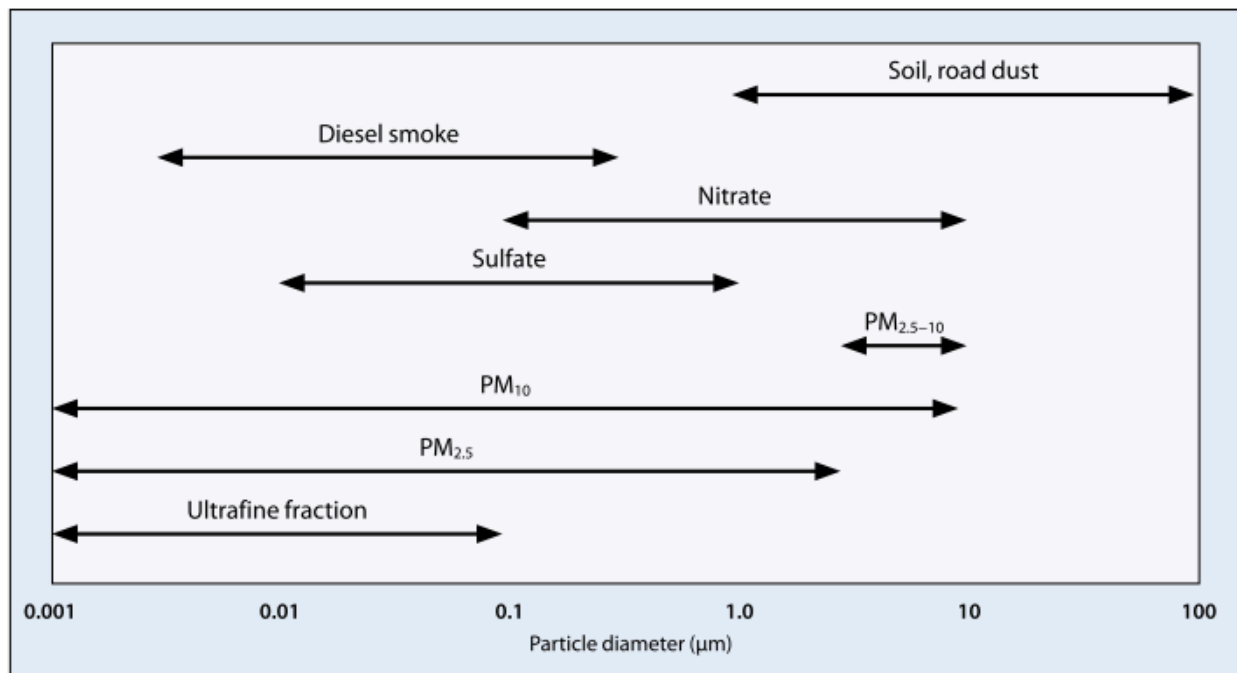
Figure 1-1: Size range of airborne particles and common components of PM (Source: Harrison *in* WHO, 2006:9).

1.6 Air quality management in South Africa

Due to its complicated history, South Africa faces air quality problems associated with both developed and developing countries. On the one hand, industrial activities and high numbers of private vehicle ownership are significant sources of emissions, whilst on the other, solid fuel burning by large numbers of the population and a strong agricultural sector also contribute significantly to air quality problems (DEA, 2009; Naiker *et al.*, 2012). This complex mix of sources pose a challenge for air quality management (AQM) in South Africa.

Current environmental legislation, including laws and regulations pertaining to air quality, are all based on the Constitution that protects each citizen's right to an environment that is not harmful to their health and well-being (DEA, 2004). This was not always the approach to AQM in South Africa however, with previous legislation widely criticized as contributing to the formation of current air pollution hotspots in the country (Naiker *et al.*, 2012).

1.6.1 The Atmospheric Pollution Prevention Act of 1965

The Atmospheric Pollution Prevention Act (APPA) passed in 1965 was the original 'best practicable means' based approach to AQM. The act primarily addressed industrial sources and had limited

control over noise, dust and vehicle emissions. Controls were mainly source-based, with air quality guidelines for stack emissions of certain pollutants, smoke control for fuel burning appliances and dust-related controls for mining and industrial activities, for example. The 'best practible means' approach involved negotiations on best practice between government and industry only, leading to criticism that this approach was biased towards industry. Methods of emission reduction were defined in terms of the act, an approach that limited innovation. APPA guidline values could not be legally enforced and the penalty system was inadequately and poorly enforced. Overall the APPA could not provide acceptable air quality (Naiker *et al.*, 2012).

With the onset of democracy in South Africa, significant policy and legislative changes led to an updated approach to environmental management. Air pollution control now needed to incorporate the principles of broader policies such as the South Africa Constitution. Figure 1-2 shows the three pieces of legislation that lead to the promulgation of the National Environmental Management: Air Quality Act (no.39 of 2004) (NEMAQA), namely the Constitution of the Republic of South Africa (1996), The National Environmental Management Act (1998) (NEMA) and the White Paper on Integrated Pollution and Waste Management for South Africa (2000) (IPWM).

1996 - CONSTITUTION

S24 – Environmental right of every citizen to live in an environment that is not harmful to their health

Air Pollution Control designated as responsibility of local government

Civil society granted more recourse for action

1998 - NEMA

Provided principles for Environmental Management and a holistic approach to the environment and impacts

Environmental justice, equity, transparency and public participation is promoted

2000 – IPWM

Turning point in pollution governance in SA

Air pollution considered synergistically with discharges to water and land

Fragmentation of policy and responsibility in pollution and waste control

Figure 1-2: Legislation that lead to the promulgation of NEMAQA (Source: Compiled from Naiker *et al*., 2012).

1.6.2   The National Environmental Management: Air Quality Act (no.39 of 2004)

The promulgation of NEMAQA lead to a major shift in AQM strategy in South Africa. A major change was the implementation of ambient air quality standards to provide a clear indication of the desired level of air quality to be achieved. This 'outcomes based' approach uses the Constitution as its departure point and defines air quality that is not harmful to health and well-being through the

ambient air quality standards as mentioned above. It further provides regulatory tools for all spheres of government to deliver these desired outcomes. Examples of these tools and regulatory measures include the declaration of priority areas and listing of activities that result in atmospheric emissions. Care was taken to design management tools is such a way as to "ensure and optimal mix of regulatory approaches that will ensure that the diversity of air pollution issues can be managed in the most effective manner, with the least possible administrative burden and use of resources (DEA, 2004:5).

Burger and Scorgie (2005) identify four main categories into which activities are grouped under NEMAQA namely objective- and standard-setting; status quo assessment and priority area delineation, control strategy preparation and implementation and progress measurement.

The National Framework for Air Quality Management (NFAQM) serves as the roadmap to achieving the aims and objectives of NEMAQA. The framework contains ambient air quality, emissions and information management standards that provides the policy outline and protocol for other spheres of government to implement direct interventions in their jurisdiction (Naiker *et al.,* 2012). The section below will discuss the National Ambient Air Quality Standards (NAAQS), Priority Air Quality Management Areas and the recently published Air Quality Offsets Guidelines in more detail, as they are very relevant in the context of this study.

1.6.2.1   National Ambient Air Quality Standards (NAAQS)

Section 24 of our Constitution (1996) provides every citizen with the right to an environment that is not harmful to their health or well-being. The NAAQS is a commitment to providing the safe environment mentioned in the Constitution, by determining acceptable levels of risk. Thus, standards provide the "yardstick" to measure whether an environment is harmful to health and well-being or not (DEAT, 2007).

The use of ambient standards to manage impacts was first recognised in the Integrated Pollution and Waste Management policy of 2000. This policy provided guidelines for the setting and implementation of standards, and describes ambient standards as:

"Ambient standards define targets for air quality management and establish the permissible amount or concentration of a particular substance in or property of discharges to air based on what a particular receiving environment can tolerate without significant deterioration" (DEAT, 2007:3).

When developing a standard for a certain pollutant, the exposure levels and environmental, social, economic conditions of a nation or region should be taken into account. Air quality standards for eight criteria pollutants have been published in terms of NEMAQA. Once a standard is implemented, assessment of compliance with said standard should be based on two considerations. Firstly, the

specified number of exceedances allowed and secondly, the maximum ambient level applicable to each exceedance. The number of allowable exceedances is determined by the required level of compliance and the fundamental units defined by the standard. Concentrations are expressed at a standardised temperature of $25^{\circ}C$ and a pressure of 101.3 kPa (DEA, 2009). Tables 1-2 and 1-3 show the NAAQS for PM_{10} as gazetted on 24 December 2009 and 29 June 2012 for $PM_{2.5}$ respectively.

Frequency of exceedance is defined in the published NAAQS as: *"a frequency (number/time) related to a limit value representing the tolerated exceedance of that limit value at a specific monitoring location, i.e. if exceedances of limit value are within the tolerances, then there is still compliance with the standard. This exceedance is applicable to a calendar year"* (DEA, 2009:7)

Table 1-2: NAAQS for PM_{10}.

Averaging Period	Concentration	Frequency of Exceedance	Compliance Date
24 hours	120µg/m3	4	Immediate – 31 Dec 2014
24 hours	75µg/m3	4	1 Jan 2015
1 year	50µg/m3	0	Immediate – 31 Dec 2014
1 year	40µg/m3	0	1 Jan 2015
The reference method for the determination of the particulate matter fraction of suspended particulate matter shall be EN 12341			

Table 1-3: NAAQS for $PM_{2.5}$.

Averaging Period	Concentration	Frequency of Exceedance	Compliance Date
24 hours	65µg/m3	4	Immediate – 31 Dec 2015
24 hours	40µg/m3	4	1 Jan 2016 – 31 Dec 2029
24 hours	25µg/m3	4	1 Jan 2030
1 year	25µg/m3	0	Immediate – 31 Dec 2015
1 year	20µg/m3	0	1 Jan 2016 – 31 Dec 2029
1 year	15µg/m3	0	1 Jan 2030
The reference method for the determination of PM2.5 fraction of suspended particulate matter shall be EN 14907			

1.6.2.2 Priority Air Quality Management Areas

In terms of Section 18 (1) of NEMAQA, the Minister or MEC of a province may declare an area as a priority area if they believe that:

(a)   "ambient air quality standards are being, or may be, exceeded in the area, or any other situation exists which is causing, or may cause, a significant negative impact on air quality in the area; and

(b)   the area requires specific air quality management action to rectify the situation" (DEA, 2004:37).

The Minister has further power to act under subsection (1) if poor air quality in an area:

(a)   "affects the national interest; or

(b)   is contributing, or is likely to contribute, to air pollution in another country;

(c)   the area extends beyond provincial boundaries; or

(d)   the area falls within a province and the province requests the Minister to declare the area as a priority area" (DEA, 2004:37)

Three Priority Areas have been declared in South Africa so far (Figure 1-3). The first area, declared on 21 April 2006, was the Vaal Triangle Air Shed Priority Area (VTAPA). The area extends over the boundaries of the Gauteng and Free State provinces and include the local municipalities of Emfuleni and Midvaal, the administrative regions of Doornkop/Soweto, Diepkloof/Meadowlands, Ennerdale/Orange Farm in the Metropolitan municipality of the City of Johannesburg in Gauteng; and the local municipality of Metsimaholo in the Northern Free State (DEA, 2006). The VTAPA is a highly industrialised area with high emissions from various polluting industries including a coal-fired power station, collieries and quarries. It is also a densely populated area with a number of large informal settlements where residential solid fuel burning is a common practice. Other sources of concern in the area are vehicle emissions, biomass burning, agricultural activities, water treatment works, landfill areas and other fugitive sources (DEA, 2008).

The Highveld Priority Area (HPA) was the second priority area to be declared on 23 November 2007. The area extends over the boundaries of two provinces (Gauteng and Mpumalanga) and contains within it the metropolitan municipality of Ekurhuleni and the Lesedi local municipality in Gauteng; and in Mpumalanga province, the local municipalities of Govan Mbeki, Dipaleseng, Lekwa,

Msukaligwa, Pixley Ka Seme, Emalahleni, Victor Kanye and Steve Tshwete (DEA, 2007). Similar to the situation in the VTAPA, the high concentration of emissions from industry (e.g. power generation, coal mining, metallurgical operations, petrochemical industry) and non-industrial sources like residential solid fuel burning, vehicle emissions and agriculture all contribute to poor air quality in the area (DEA, 2012).
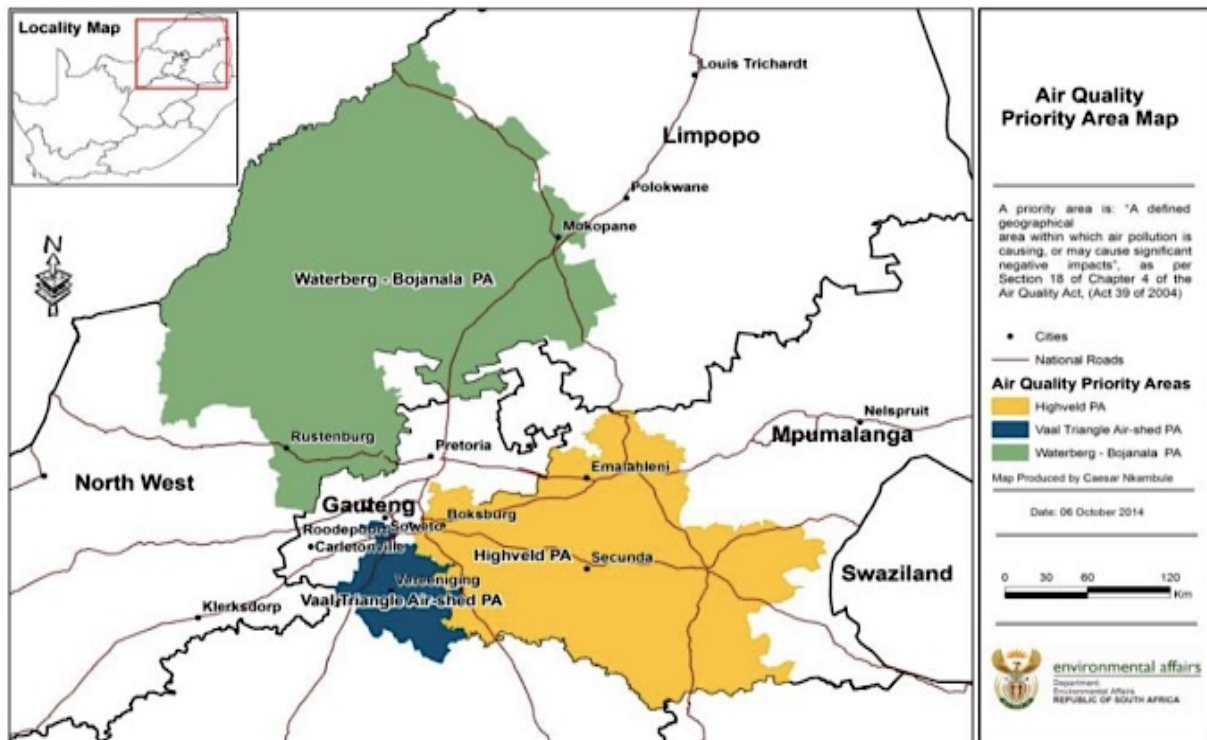
Figure 1-3: Map of the three priority air quality management areas in South Africa (Source: Khumalo, 2016).

A third priority area, the Waterberg-Bonjala Priority Area (WBPA) was declared on 15 June 2012. This area borders with Botswana and extends over the Limpopo and North-West provinces. The area includes the local municipalities of Thabazimbi, Modimolle, Mogalakwena, Bela-Bela, Mookgopong and Lephalale in Limpopo and in the North-West Province, those of Moses Kotane, Rustenburg and Madibeng. The WBPA was declared due to two major concerns: 1) that the large unexploited coal reserves in the Waterberg district municipality and neighbouring Botswana could lead to mining activities that would negatively impact air quality in the area and, 2) that the presence of two operating power stations and the planned development of more coal-fired power plant capacity in both South Africa and Botswana pose a threat to ambient air quality in the region. Declaration of the WBPA ensures that all management planning in the area will include consideration of current and future threats to air quality in the region (DEA, 2015).

Two of the priority areas, the HPA and VTAPA are included in the study area for this research. Air quality in these areas will be discussed in more detail in subsequent sections of this document.

1.6.2.3 Air Quality Offset guidelines

The Air Quality Offsets guidelines were published on 18 March, 2016 in terms of section 24J (a) of the National Environmental Management Act (NEMA), 1998 (no. 107 of 1998). It is hoped that offset programmes could be a complimentary measure to help "address complex pollution sources by allowing concerted efforts by both government and polluting industries to clean up the air" (DEA, 2016:7). The guidelines define offsets in the AQM context as:

"an intervention, or interventions, specifically implemented to counterbalance the adverse and residual environmental impact of atmospheric emissions in order to deliver a net ambient air quality benefit within, but not limited to, the affected air shed where ambient air quality standards are being or have the potential to be exceeded" (DEA, 2016:13).

Offsets are included as an option during the Air Emission Licensing (AEL) process and licensing officials may consider including offsets as a condition of and AEL under certain circumstances. Firstly, offsets may be recommended during an application for the postponement of compliance timeframes, but only when there is sufficient evidence that 1) there is no technology available globally to reduce air emissions from the listed activity, 2) that the plant in question will be decommissioned in 10 years from postponement and, 3) if investment in control measures cannot be made due to restrictions by other national strategic and legislative requirements. Secondly, offsetting could be included in an AEL during an application for a variation of a license and lastly, during an application for an AEL in areas where NAAQS are or are likely to be exceeded (DEA, 2016).

The implementations of offsets have been a requirement of some AELs since April 2015 and several pilot offset programmes have been implemented specifically targeting household emissions (Langerman *et al.,* 2016). A few challenges and shortcomings were identified during the course of these projects, some regarding the implementation of offsets and others regarding quantifying the impacts of interventions. (Burger and Piketh, 2016; Garland et al., 2016; Langerman et al., 2016)

Burger and Piketh (2015) proposed effective pollution intake as a means to calculate the amount of reduction needed for an intervention to be deemed successful. This approach involves using the amount of pollution inhaled by the population exposed to emissions near a facility to calculate the corresponding amount by which an offset should reduce effective pollution intake in a given community. Garland et al. (2016) propose an accounting approach that involves firstly defining the outcome for which the accounting is oriented (e.g. improved ambient air quality), followed by a

definition of the project activities (pre- and post- intervention activities). Next, a baseline scenario should be defined and a description of baseline impacts given. The project scenario (post-implementation) must then be described and its impacts calculated. The impact of the intervention will be the difference in the impacts calculated for the baseline and project scenarios.

They propose four approaches for the calculation of project impacts:

- Particulate equivalence to define ambient concentrations (comparing intra pollutant offsets where one pollutant is a precursor for the other, e.g. offsetting SO_2 emissions from power generation with a reduction in PM emissions from solid fuel burning);

- Standards weighted pollutant intake to determine exposure;

- Equivalent short-term mortality risk estimation to determine impacts, and

- Burden of disease equivalence, to determine the effect of a polluting activity on a population

The debate about the measurement of offset effectiveness continues, but the general consensus seems to be that the impacts on human health should be included. The principles and challenges of offsetting are discussed in more detail in the introductory sections of Manuscript 1 (Chapter 3) and Manuscript 3 (Chapter 5) respectively.

1.7 Air Quality on the Highveld

Air quality remains a concern over the Highveld, with frequent monitored exceedances of the NAAQS for PM_{10} and $PM_{2.5}$ in both the HPA and VTAPA, and some exceedances for SO_2 in the HPA where a large number of power stations are situated (Figures 1-4, 1-5 & 1-6) (Khumalo, 2016). Nitrogen Oxide (NO_x) and Ozone (O_3) are two other pollutants of concern in both areas.

As SO_2 is a gaseous pollutant, the major route of exposure is inhalation. Exposure can also occur to a lesser extent through skin contact. Most inhaled SO_2 only penetrates the nose and throat, with only minimal amounts reaching the lungs. Exposure increases with the volume of air inhaled, and studies have shown that exercise can increase the acute health effects. Some individuals are also more sensitive to the effects of SO_2 (e.g. asthmatics, the elderly and children) (Raghunandan *et al.,* 2008).

Oxides of nitrogen are considered criteria pollutants in South Africa and most other regions around the globe. Industrial emissions of NOx over the South African Highveld have been reported to be among the highest global anthropogenic emissions. In Figure 1-7 the high NO_2 concentrations over the Highveld are clearly discernible on images retrieved from the SCIAMACHY satellite in 2006. The Highveld region accounts for about 90% of NO_x emissions in South Africa (Collet *et al.,*2010).

Although not harmful to human health at normal mixing ratios, they are precursors to the formation of tropospheric ozone (O_3), nitric acid (HNO_3) and particulate nitrate (NO_3) a component of PM. These pollutants again contribute to the formation of smog, acid rain and global radiative forcing (Ojelede *et al.*, 2008).
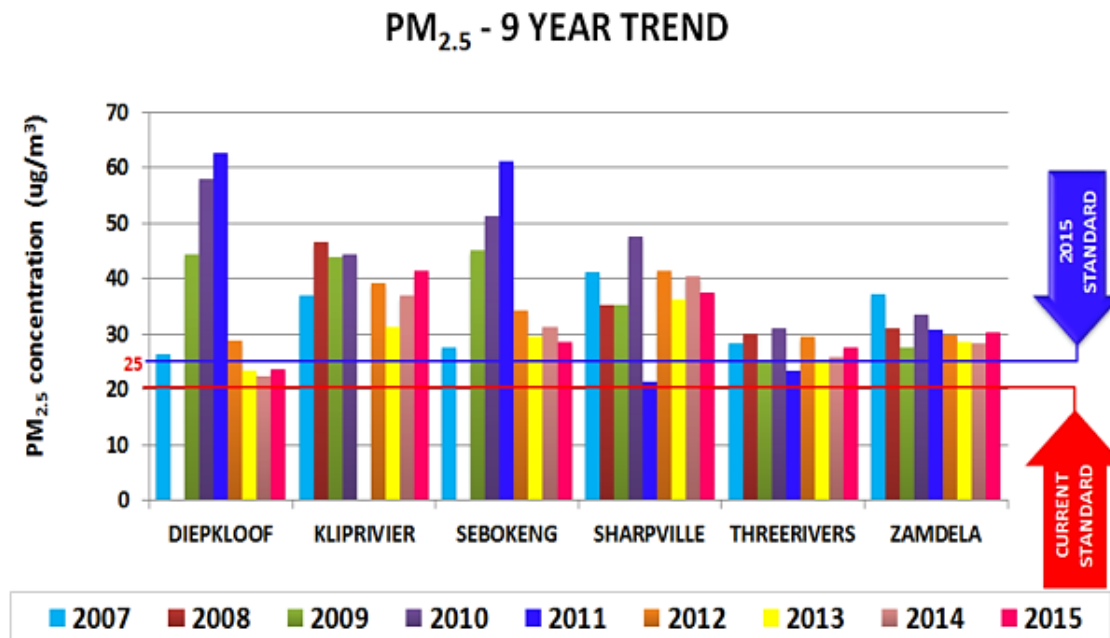
Figure 1-4: Monitored mean annual PM2.5 concentrations and frequent exceedances of the NAAQS over the VTAPA over 9 years (Source: Khumalo, 2016)
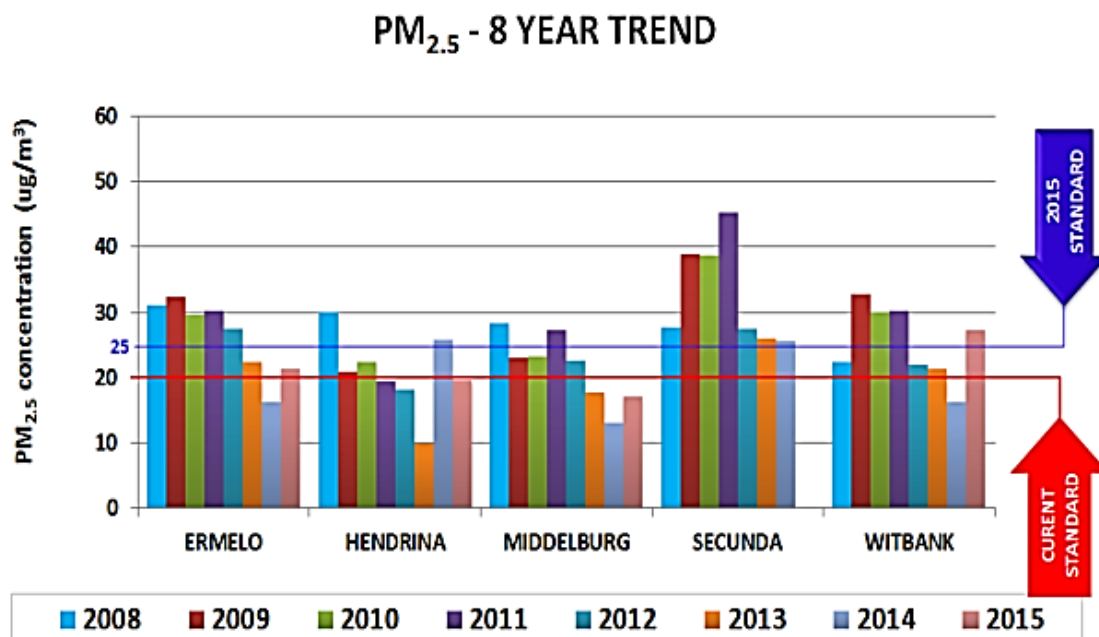
Figure 1-5: Monitored mean annual PM2.5 concentrations and frequent exceedances of the NAAQS in the HPA over 8 years (Source: Khumalo, 2016).
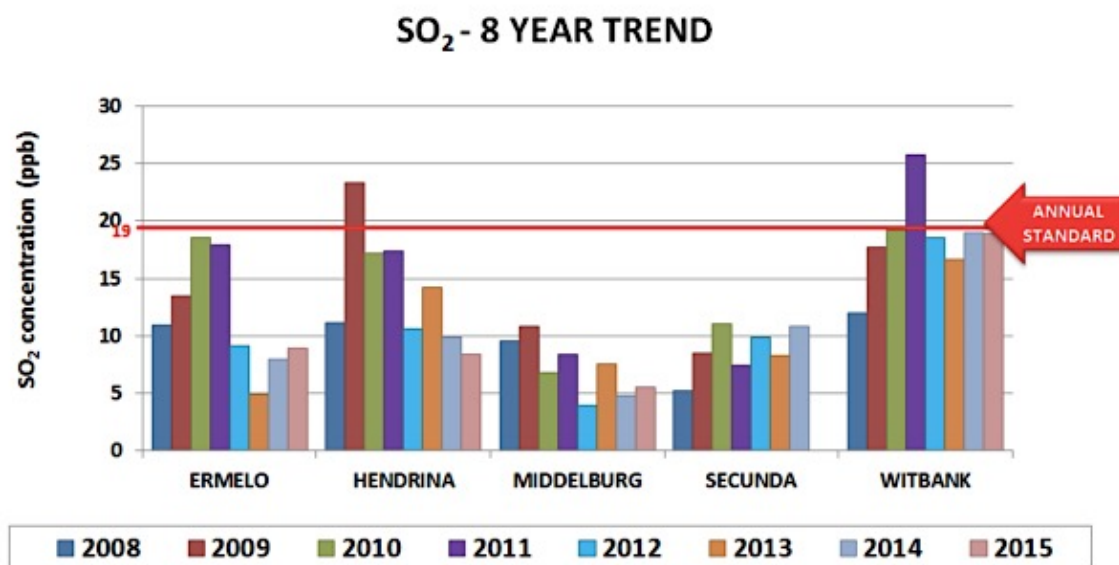
Figure 1-6: Monitored mean annual concentrations and exceedances of the NAAQS in the HPA over 8 years (Source: Khumalo, 2016).
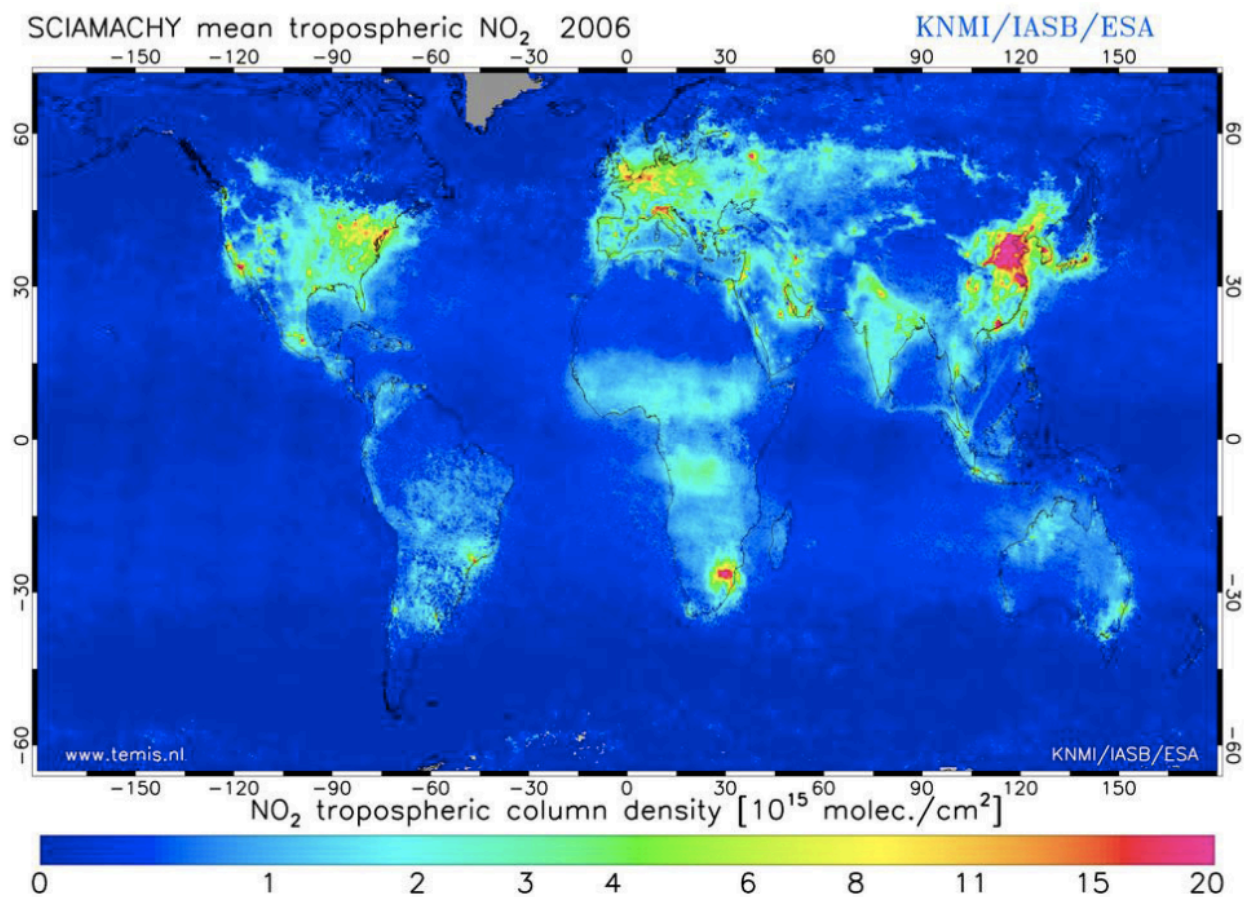
Figure 1-7: SCIAMACHY image of mean tropospheric vertical column density for 2006 (Source: Collett et al., 2010).

Even though power generation is the major source of NOx emissions in the area, studies have also shown that residential coal combustion and vehicle emissions are a significant source of NOx in the region, and because of their low level emission, pose a greater threat to human health. Lourens *et al.* (2012) found that traffic emissions and residential coal burning around the cities of Johannesburg and Pretoria contribute significantly to NO_2 levels in the area. Two distinct peaks were observed daily (06:00-9:00 and 17:00-21:00), with higher NO_2 concentrations than the Highveld area of high concentration, coinciding with peak traffic hours in the city.

Meteorological conditions in the area exacerbate air quality problems, due to the prevalence of a subtropical high that leads to weak pressure gradients and the formation of inversion layers that lead to the accumulation and re-circulation of pollutants and limits their vertical dilution (Wenig *et al.*, 2002). These inversions are especially prevalent in the winter months, when low temperatures increase the demand for heating (and solid fuel burning). Peaks in $PM_{2.5}$ concentrations during typical heating and cooking times are frequently measured, and more pronounced during colder months (Burger & Piketh, 2015). Figures 1-8 and 1-9 illustrate the seasonal variability of monitored $PM_{2.5}$ concentrations in both the HPA and VTAPA.
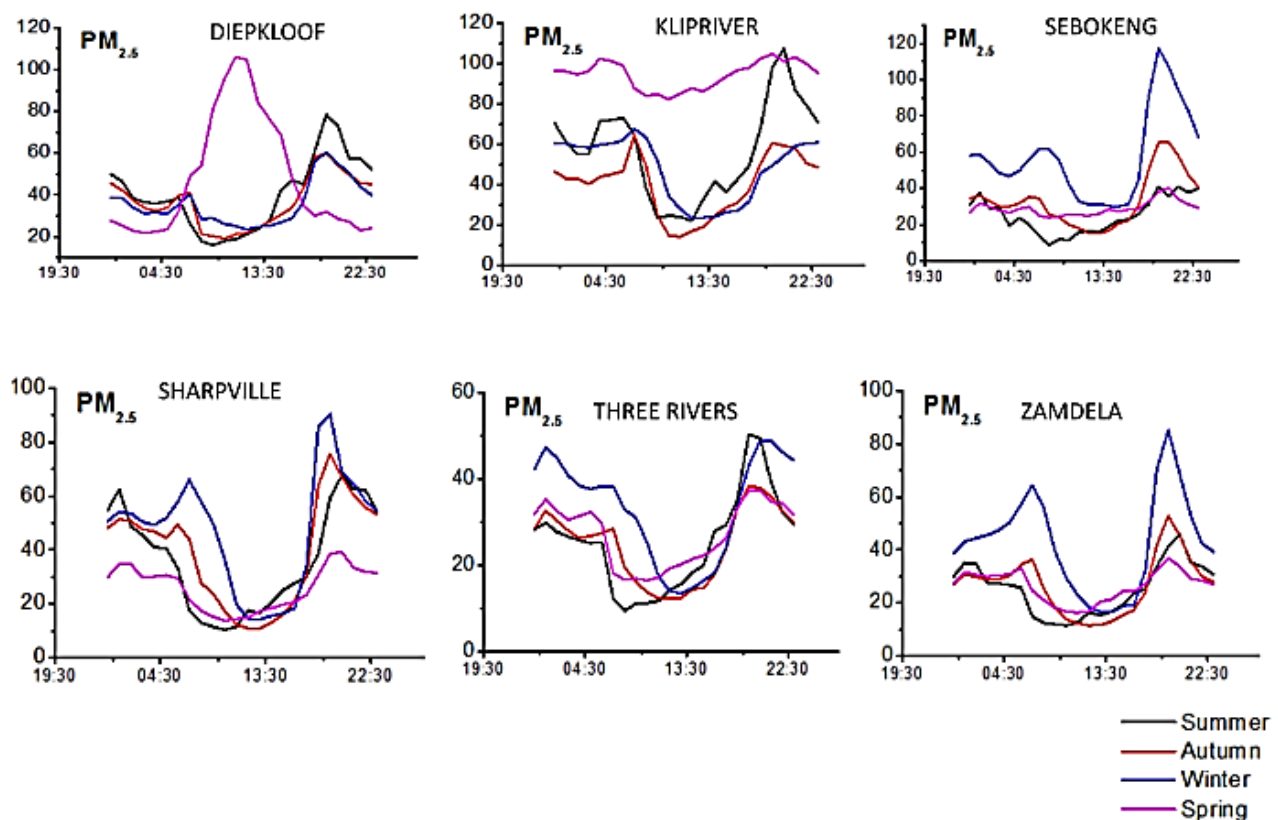
Figure 1-8: Seasonal variations of $PM_{2.5}$ concentrations in the VTAPA (Source: Khumalo, 2016).
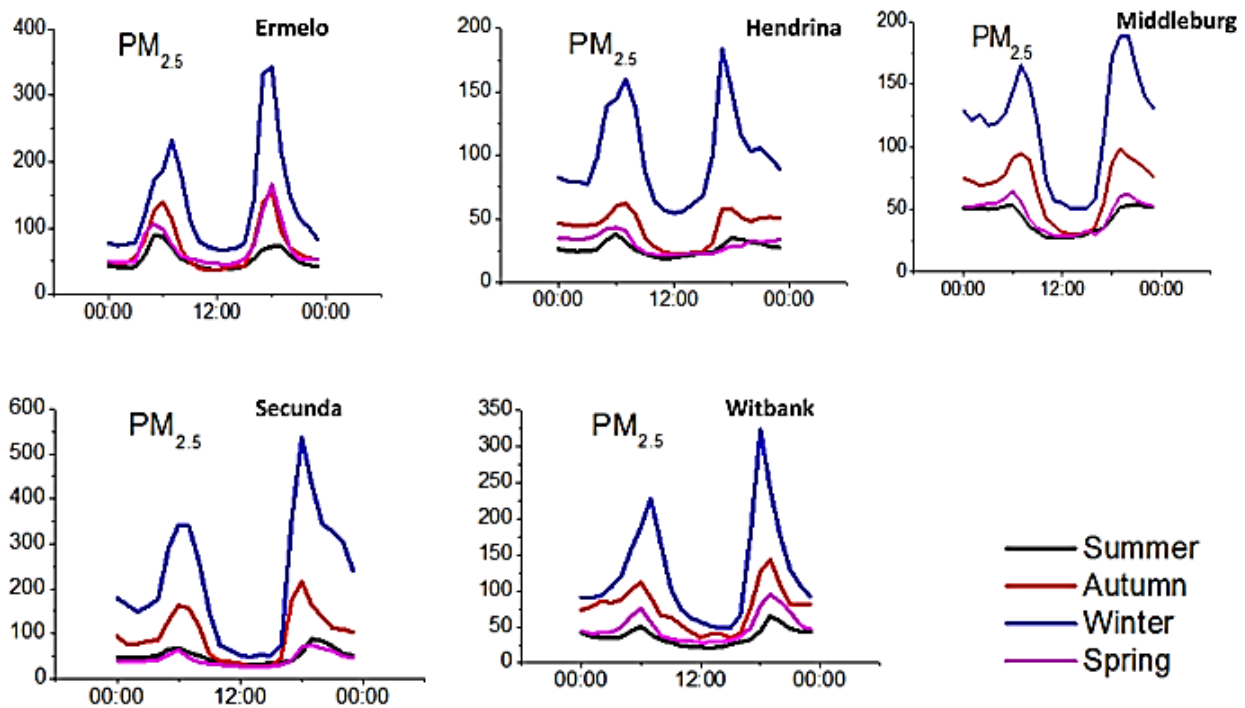
Figure 1-9: Seasonal variations of PM₂.₅ concentrations in the HPA (Source: Khumalo, 2016)

The frequent presence of absolutely stable layers over the whole of South Africa also influence the dispersion and transport of pollutants over the Highveld. These layers are most often present at levels where decoupling occurs between circulations of the lower middle and middle upper troposphere (at ~850 hPa over coastal regions and at ~700 hPa, ~500 hPa and ~300 hPa throughout the troposphere). These stable layers act as boundaries in the upper air and impede the vertical dispersion of pollutants as the upward motion of air is inhibited (Freiman & Tyson, 2000). Absolutely stable layers have consequences for pollution concentrations at both the local and regional scales. At the local scale, absolutely stable layers can lead to high concentrations of pollutants. Should pollutants penetrate through one layer, accumulation will once again occur below the next one.

This accumulation can frequently be seen with the naked eye during winter months over the interior at the 700 hPa and 500 hPa levels. The brown haze belt often seen over the Johannesburg area is a result of these stable layers, for example (Freiman & Tyson, 2000).

The stable layer observed with highest frequency over the interior of the country occurs at 500 hPa. This layer also controls the distribution of pollutants over South Africa and plays an important role in the medium-to long range transport and recirculation of aerosols and gasses. Pollutants from the Johannesburg area are recirculated over the city or transported to the Vaal Triangle area, contributing pollutants to an area already known for air quality issues, for example (Freiman & Tyson,

2000). The appearance of this layer is more frequent in winter when emissions of pollutants are at their highest over the Highveld (Figure 1-10). This can have significant implications for not only visibility over the region, but also for human exposure to the harmful health effects of air pollution and environmental degradation.
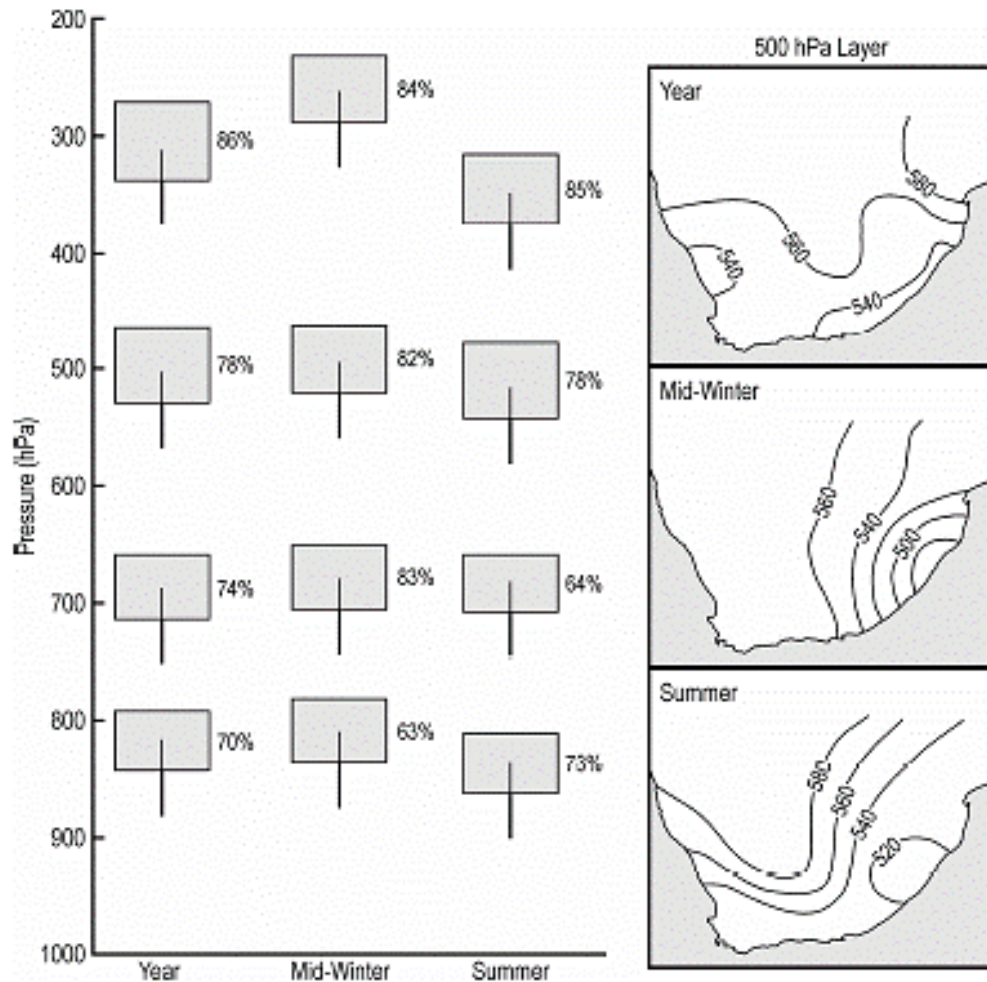
Figure 1-10: The seasonal frequency and height of absolutely stable layers over South Africa (Source: Cosin & Tyson *in* DEA, n.d).

1.8   Air pollution and health

In May 2015, the 68th World Health Assembly named air pollution "the world's single biggest environmental health risk" and adopted a resolution to address the health impacts of air pollution (WHO, 2015a). As the majority of harmful air pollutants are emitted by anthropogenic activities, air pollution is specifically named as "one of the main *avoidable* causes of disease and death globally". Each year, exposure to HAP and ambient air pollution AAP are estimated to cause 4.3 million and 3.7 million deaths respectively. The distribution of these health effects however, is not equal, as the

"root causes" of air pollution are recognised to be predominantly socio-economic in nature. A large number of factors including socio-economic status, gender, age, genetic predisposition, pollutant source and composition and physical location will influence a person's levels of exposure and their physical response to this exposure (WHO, 2015b). Thus, in order to tackle the health burden associated with air pollution, all the determinants of health need to be addressed in order to truly improve air quality and reduce health inequity.

1.8.1   Exposure to air pollution

Air pollution levels need not necessarily be very high to pose a risk to human health. Due to the large number of people exposed around the globe on a daily basis, the associated levels of morbidity and mortality is significant. Human exposure is defined as "the event when a person comes into contact with a pollutant of a certain concentration during a certain time" (Ott, 1982 *in* Jansen & Mehta, 2006:62).

Exposure is considered to be a better environmental health risk indicator than ambient air quality measurements, as exposure (past and present) triggers all environment related health impacts responsible for the current air-pollution related burden of disease. Exposure to air pollution does not only refer to inhalation, but to contact with any part of the human body (e.g. skin or eyes) (Jansen & Mehta, 2006). Exposure occurs along a conceptual "environmental pathway" between concentration and dose, as illustrated in Figure 1-11 below.

Figure 1-11: The conceptual environmental pathway of exposure (Source: Jansen & Mehta, 2006).

In the figure above concentration refers to a quantitative measure of the amount of pollutant within an environmental medium, in this context, air. Dose refers to the amount of a pollutant that enters the body by crossing one of the body boundaries. The dose is again defined by the type of exposure, the characteristics and concentration of the pollutant of concern and the physiological characteristics (level of activity, pre-existing conditions etc.) of the exposed person/s.

As mentioned above, human exposure occurs wherever people spend their time. Human exposure is thus influenced by the air quality of the environments where people spend time, as well as the amount of time they spend in these environments. People are exposed to different pollutant concentrations as they move between places, often called microenvironments, throughout their day.

Janssen and Mehta (2006) roughly divide the world into different microenvironments namely, indoor versus outdoor environments, developed versus developing countries and urban versus rural areas.

People everywhere spend most of their time indoors, but differences in time exposed between urban and rural population exposure vary greatly between developed and developing countries. As seen in Figure 1-12, the rural indoor environment is the microenvironment where the greatest exposure occurs in terms of person-hours globally.
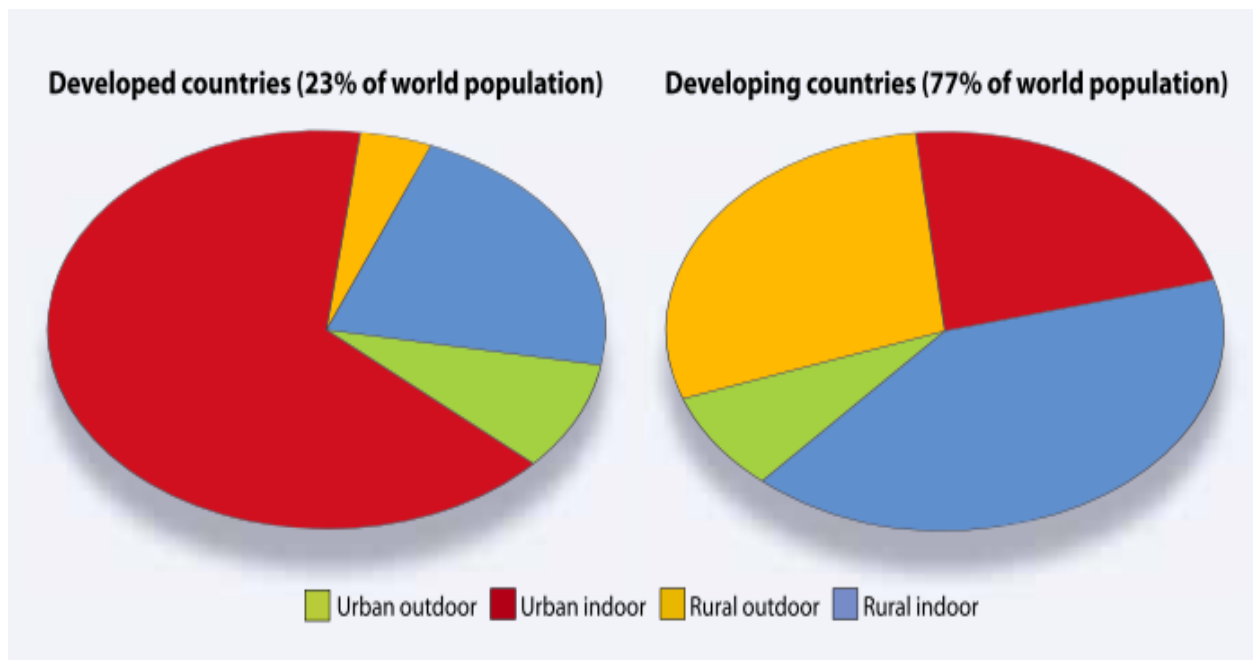
Figure 1-12: The division of global person-hours into eight microenvironments (Source: Janssen & Mehta, 2006:63).

In the South African context, human exposure to emissions from residential solid fuel burning also remains a key concern. These emissions occur in both urban and rural settings, and in densely populated low-income urban settlements they contribute significantly to poor indoor and ambient air quality. These areas are characterised by high air pollution source densities and high population densities, resulting in very high levels of exposure (DEA, 2009).

The highest concentrations of both PM_{10} and $PM_{2.5}$ on the Highveld are measured in these areas during winter when residents burn more solid fuels for cooking and heating (Hersey *et al.*, 2015). In densely populated low-income settlements on the Highveld, residential solid fuel burning has been shown to contribute to between 45% - 88% of annual mean PM concentrations at the local scale (Engelbrecht *et al.*, 2002; Scorgie *et al.*, 2003), and is thus a significant source of air pollution in these areas.

1.8.2   The determinants of health

The definition of health as we use it today was first formulated in 1948 by the World Health Organization as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (Huber *et al*., 2011). This definition alludes to the fact that health is very much determined by the environment (physical, social and cultural) where people live and not only by behaviours or lifestyle choices (Quigley *et al*., 2006). Table 1-4 below provides a brief description and examples of the determinants mentioned above.

Table 1-4: The determinants of health.

Categories of health determinants	Examples of specific determinants
INDIVIDUAL: These determinants are the genetic, biological, behavioural and/or circumstantial factors unique to each individual	• Age and gender • Employment status, life skills and income • Diet, alcohol intake and levels of physical activity
SOCIAL AND ENVIRONMENTAL: These determinants refer to physical, community and/or economic conditions	• Quality of water, soil and air • Quality of housing • Land use and/or urban design • Access to basic services
INSTITUTIONAL: Determinants that relate to the quality and capacity of public services	• Availability of services (e.g. health, transportation, communication, education, employment) • Public health and environmental legislation • Health and environmental monitoring systems

Source: Quigley *et al.,* 2006:2.

It is clear from the descriptions and examples above that many factors that influence health and well-being are very often not within the control of affected individuals or communities. The WHO (2016b:2) describes these health inequities as "unjust and avoidable", and urges member states to address the circumstances that shape these inequities - the distribution of money, power and resources.

Integrated policy approaches at all levels (global, regional and local) in different sectors are necessary to address the complexities of health inequity. These inequities very often depend on decisions made in other sectors and are connected to various interrelated issues involving for example education, the environment, governance, employment, housing, social security, food, water, transport and energy (WHO, 2016). This is echoed by (Quigley *et al*., 2006) who contend that not considering health in the development planning process often passes "hidden costs" on to

communities by reducing their well-being and increasing their burden of disease. It is very often disadvantaged and marginalized groups that carry the majority of these "hidden costs" as is frequently the case in the air quality context in South Africa. Here, low-income communities are not only more likely to be exposed to higher levels of air pollution, but are also more vulnerable to the adverse health effects of this exposure due to poverty and underdevelopment in their residential areas (Mathee & Wright, 2014).

The Commission on Social Determinants of Health (CSDH), set up by the WHO, developed a conceptual framework to better understand the complexities involved (Figure 1-13) and better inform decision and policy making. A key aim of this framework is "to highlight the difference between levels of causation, distinguishing between the mechanisms by which social hierarchies are created, and the conditions of daily life which then result" (Solar & Irwin, 2010:4).
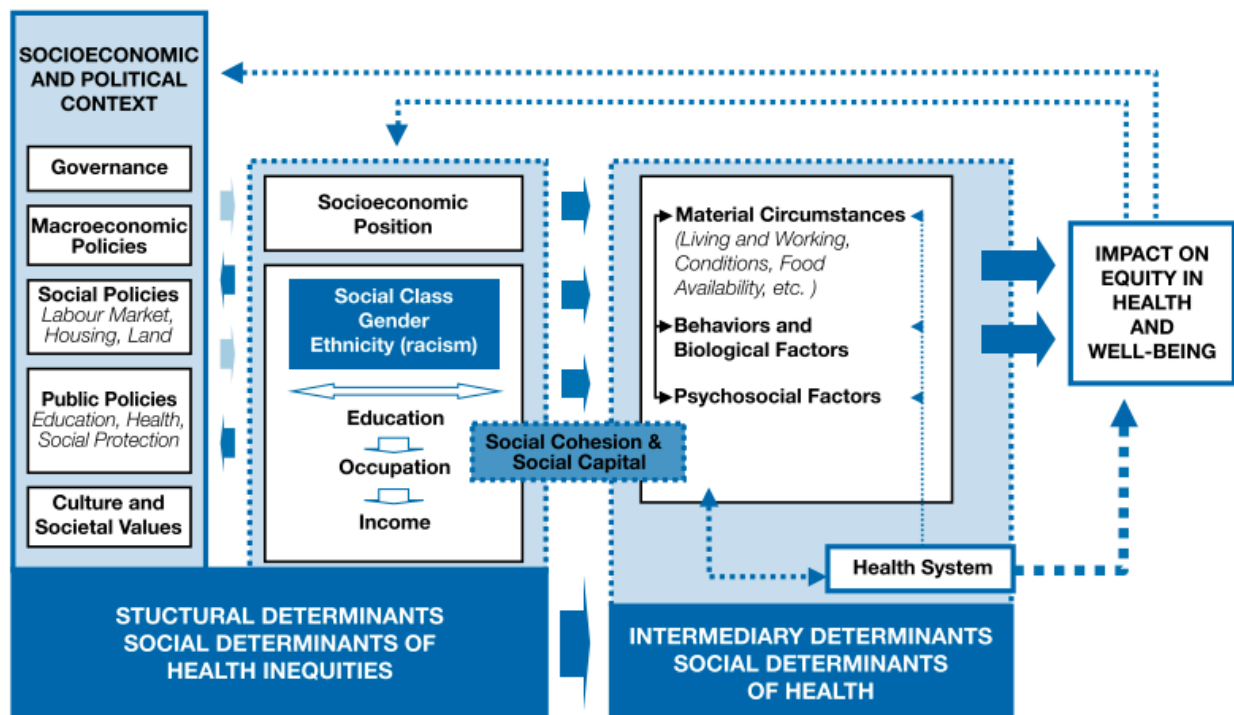
Figure 1-13: Conceptual framework showing the social determinants of health and how they interact (Source: Solar & Irwin, 2010:6).

The CSDH conceptual framework by Solar and Irwin (2010) (Figure 1-13) illustrates how the various social, political and economic mechanisms interact to create the socioeconomic positions that populations are stratified by according to their race/ethnicity, income, occupation, gender and education.

1.8.2.1 Social determinants of health in South Africa

In South Africa, the legacy of apartheid, where policies that created extreme inequality and inequity were in place for over four decades, still affects all aspects of society, including the health system and health status of our population. Addressing these inequities is a major objective of the National Department of Health's primary health care re-engineering strategy, but according to Scott *et al.* (2017:77), "the translation of this policy commitment to programmatic action at different levels in the health system and in partnership with other sectors remains elusive". Mathee & Wright (2014) share this sentiment and argue that the South African health sector lacks the institutional arrangements, expertise and capacity to promote and capitalise on the potential benefits of inter-sectoral action.

The environments and quality of housing where people live is one of the strongest determinants of public health. Despite efforts by government, many residents of low-income settlements are still living in conditions of extreme poverty, with less access to quality basic services like healthcare, sanitation, electricity and education (MacLean, 2005). Even if households have access to certain basic services, they are not always able to afford to use or access them. This has especially been shown to be the case with electricity use.

Currently, 85% of South Africans have access to electricity (StatsSA, 2014), but many low-income households can't afford to use it as their only energy source. These households supplement their energy needs by burning solid fuels for cooking and/or heating purposes. Solid fuels are cost-effective alternatives and often more convenient, as the same appliance is used for cooking and space heating simultaneously (Balmer, 2007). Figure 1-14 below shows the distribution of main sources of energy used for cooking by households in South Africa from 2002 - 2013. Although the percentage of households using electricity for cooking increased from 58% in 2002 to 78,4% in 2013, the use of solid fuels remains widespread enough to warrant further action (StatsSA, 2014).

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
□ Other	1,3	1,2	1,6	0,8	0,6	0,6	0,6	0,5	2,4	3,0	1,3	0,8
■ Coal	3,0	2,7	2,4	2,4	2,1	2,2	1,9	1,4	1,2	0,9	0,8	0,4
□ Wood	19,3	18,7	17,9	15,3	14,0	13,8	15,7	15,1	13,7	12,7	11,6	10,5
□ Paraffin	16,2	15,9	15,5	16,6	16,0	14,2	10,3	9,5	8,4	7,1	7,8	6,8
■ Gas	2,2	1,6	1,7	1,8	2,3	2,3	3,0	2,2	2,2	2,1	3,3	3,2
■ Electricity	58,0	60,0	61,0	63,1	65,1	67,1	68,6	71,4	72,1	74,2	75,2	78,4
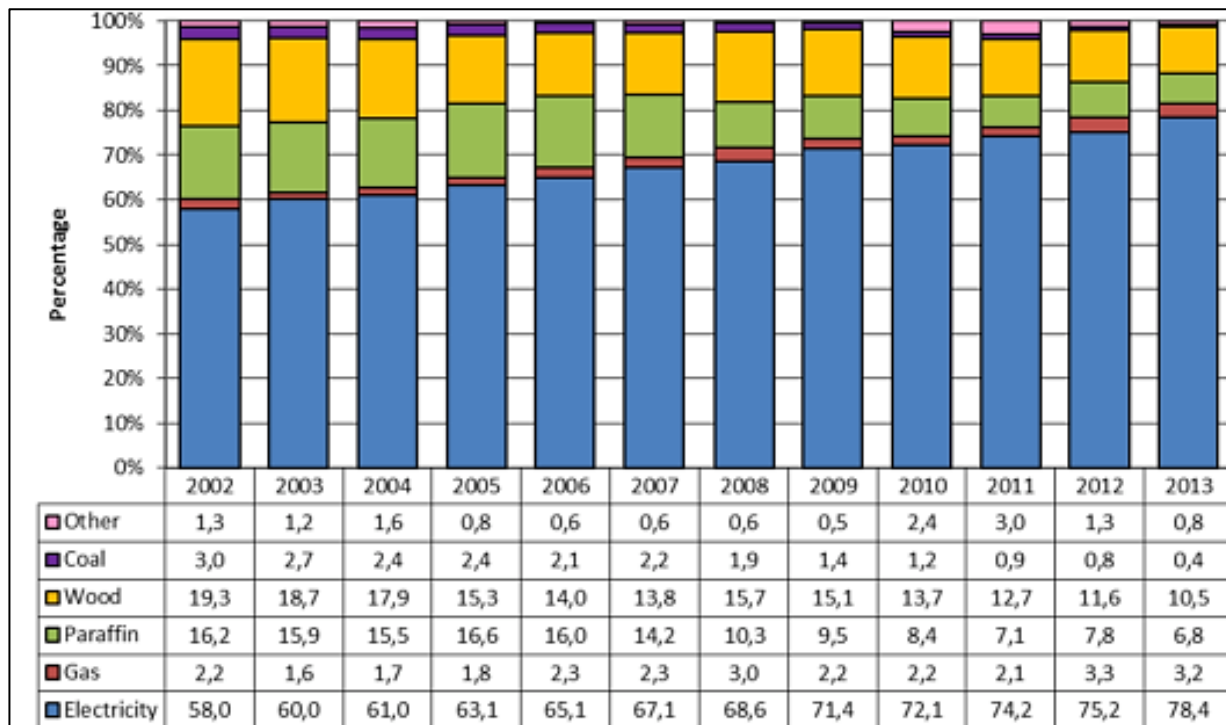
Figure 1-14: Percentage distribution of main sources of energy used for cooking in South Africa from 2002-2013 (Source: StatsSA, 2014).

The type of fuel used by households also varies greatly through time and space. The provincial distribution of fuel type used in South Africa (Figure 1-15), illustrates this variability. More residents of rural provinces such as Limpopo, Eastern Cape and KwaZulu-Natal reported using alternative sources of fuel (mostly wood and paraffin) than provinces with more urban populations. Mpumalanga is the province where the highest number of residents reported using coal, this is due to the proximity of coalfields making it an easily accessible fuel source (Barnes *et al.*, 2009; StatsSA, 2014). This variability is even more pronounced at the local level, where the steep population gradients typical in many urban and peri-urban areas result in high spatial variability of energy use and emissions within cities and towns (Cairncross, 2016).

	WC	EC	NC	FS	KZN	NW	GP	MP	LP	RSA
☐ Other	0,4	0,7	0,6	0,6	0,8	0,6	1,2	0,2	0,3	0,8
☐ Coal	0,0	0,0	0,1	0,8	0,5	0,0	0,3	2,8	0,1	0,4
☐ Wood	0,6	13,2	4,3	3,4	16,0	8,4	0,7	15,4	41,4	10,5
☐ Paraffin	2,1	10,7	5,9	4,6	4,9	8,3	10,3	4,0	3,5	6,8
☐ Gas	8,5	4,0	5,3	1,8	2,4	1,6	2,9	1,9	1,2	3,2
☐ Electricity	88,4	71,5	83,9	88,8	75,5	81,1	84,6	75,6	53,5	78,4
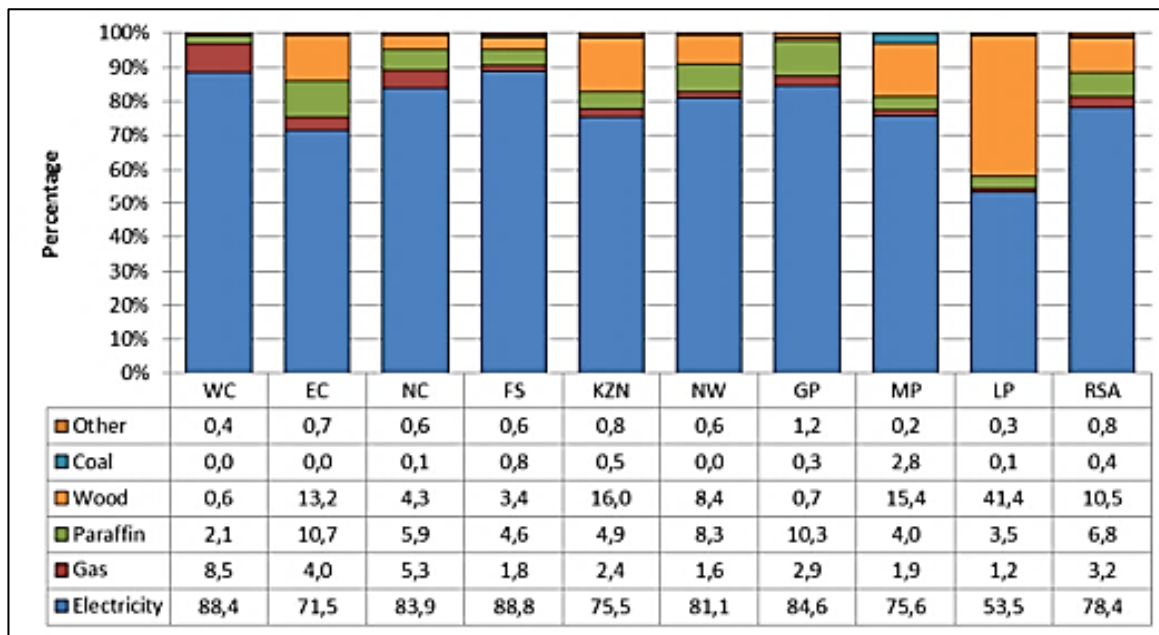
Figure 1-15: Percentage distribution of main sources of energy used for cooking by province, 2013 (Source: StatsSA, 2013).

Historical housing backlogs, urbanisation, immigration and natural population increase will make meeting the growing demand for housing and basic services even more challenging. As urbanisation continues to increase, this need will grow. Urbanisation in Africa is driven by poverty and as such, the highest rates of urban growth are occurring in areas of existing poverty. As the "health of nations will be increasingly determined by that of their urban populations" (Mathee & Wright, 2014:106), a serious need for action exists in order to ensure cost-effective solutions and to protect public health.

Wright and Diab (2011) propose an approach that goes beyond only considering the presence of communities in air quality management planning to also include specific community characteristics such as their vulnerability to the negative impacts of air pollution exposure. Vulnerability varies between and within communities and is influenced by various factors including age, gender, living conditions, socio-economic status and access to social support and services. They propose a framework to aid air quality management planners identify high-risk communities in order to apply a more focused management approach. This approach could lead to the development of interventions to reduce adverse health impacts in identified communities. The framework uses indicators related to five main themes in order to prioritize air quality management approaches in high risk areas. The five themes they identified are air pollution sources, ambient air pollution levels, air pollution potential, community awareness, perceptions, observations and actions and lastly, population vulnerability factors. The five themes and their indicators are presented in Figure 1-16.

They divide population vulnerability into five further subsections: general population demographics, health, exposure, socio-economic and environmental disasters and risks. Population demographics can be used to measure increased vulnerability to health hazards as they directly or indirectly influence the abilities of individuals, households and communities to cope with external shocks and/or stresses. Population demographics that can be used as indicators of increased vulnerability include enumeration area (EA) type, population density, sex, age and socio-economic status (levels of education, annual household income and employment status).
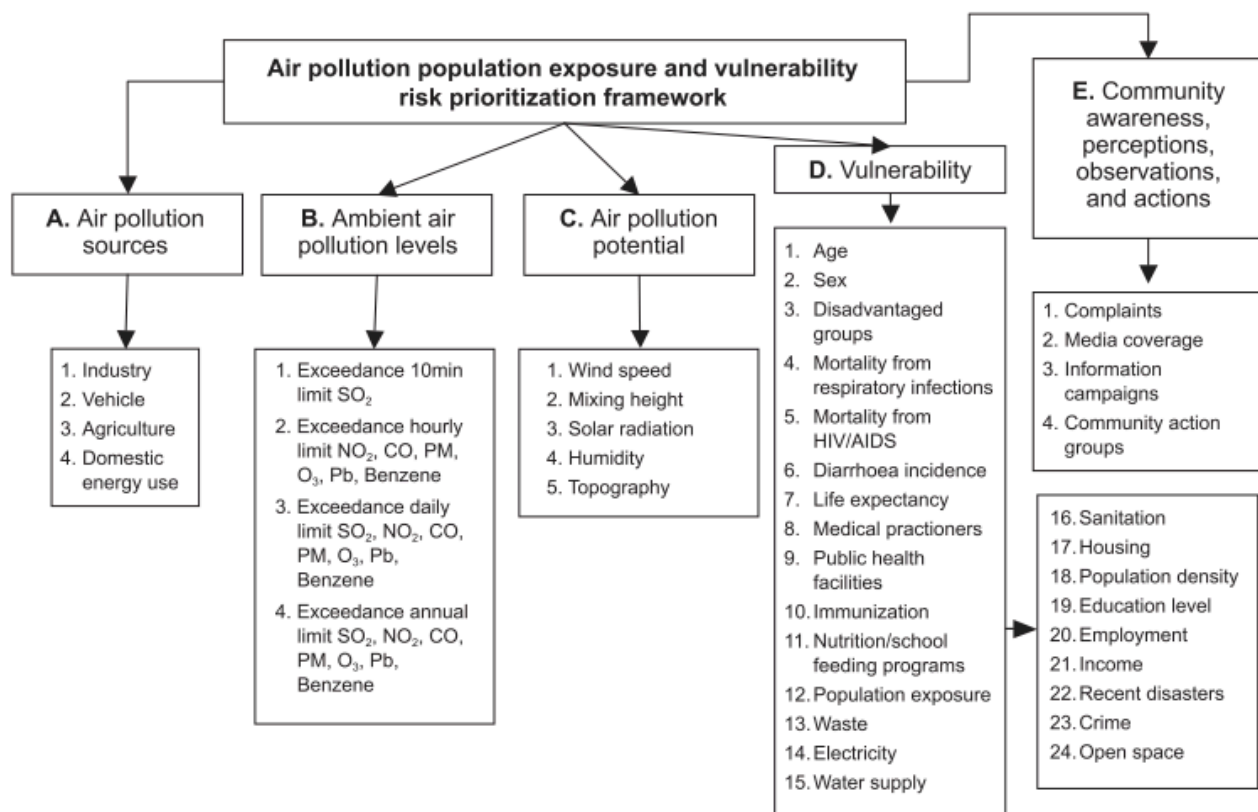
Figure 1-16: The air pollution population exposure and vulnerability risk prioritization framework (Source: Wright & Diab, 2011:57).

The incidence and prevalence of disease, nutrition, life expectancy and access to health care are also considered important indicators. Levels of basic service provision (water and sanitation, waste removal and energy supply) are also important indicators of as the absence or inadequate supply of these services can lead to health hazards such as waterborne diseases and exposure to household air pollution (Wight & Diab, 2011).

Hayes (2017:16) agrees that a change in our approach to air quality management is needed because people are too often absent in the models and scenarios used to predict air quality concentrations and impacts. She eloquently argues that:

"The air quality discourse and management practices needs to go beyond the traditional 'where and what' approach to provide a new perspective and a new geography of pollution based instead on 'who and why' which considers citizens daily activities, behaviour and practices which will clearly allow the connection to be made between pollution and behaviour, and link these to the various practices that constitute everyday life within our cities".

1.8.3 Adverse health impacts of Particulate Matter

Table 1-5: Criteria pollutants and their adverse health effects.

Criteria Pollutant	Associated adverse health impacts
Sulphur Dioxide (SO_2)	• Inflammation of airways • Bronchitis • Decreased lung function • Asthma exacerbation
Nitrogen Dioxide (NO_2)	• Decreased lung function • Asthma exacerbation • Increased susceptibility to viral and bacterial infections • Inflammation of airways
Carbon Monoxide (CO)	• Headaches and dizziness • Nausea and vomiting • Anaemia • Respiratory disease • Premature death
Ozone (O_3)	• Damage to lung tissue • Reduced lung function • increased susceptibility to viral and bacterial infections
Benzene (C_6H_6)	• Leukaemia • Aplastic anaemia, Myelodysplastic syndrome • Genetic defects
Lead (Pb)	• Reduced central nervous system function • Reduced kidney- function and -failure • Blood and bone marrow disorders • Reproductive system disorders

(Source: Compiled from Brunekreef & Holgate, 2002; DEA, 2009; WHO, 2006).

As defined in the scope of this study, the pollutant of focus for this analysis is $PM_{2.5}$. The health impacts of this pollutant will thus be discussed in detail.

It must be noted though, that all criteria pollutants listed in the National Ambient Air Quality Standards (NAAQS) are regulated specifically because they have been shown to have adverse

impacts on human health (DEA, 2009). Table 1-5 provides a summary of the main impacts associated with each criteria pollutant.

Both PM_{10} and $PM_{2.5}$ impact health as they contain particles that are small enough to be inhaled and penetrate the respiratory system. PM_{10} typically doesn't go past the upper respiratory tract, whilst $PM_{2.5}$ and UFP penetrate much deeper into the lower respiratory tract where toxins contained in particles can be absorbed as illustrated in Figure 1-17 (Guarnieri & Balmes, 2014). For this reason, exposure to $PM_{2.5}$ is considered a stronger risk factor for both morbidity and mortality.
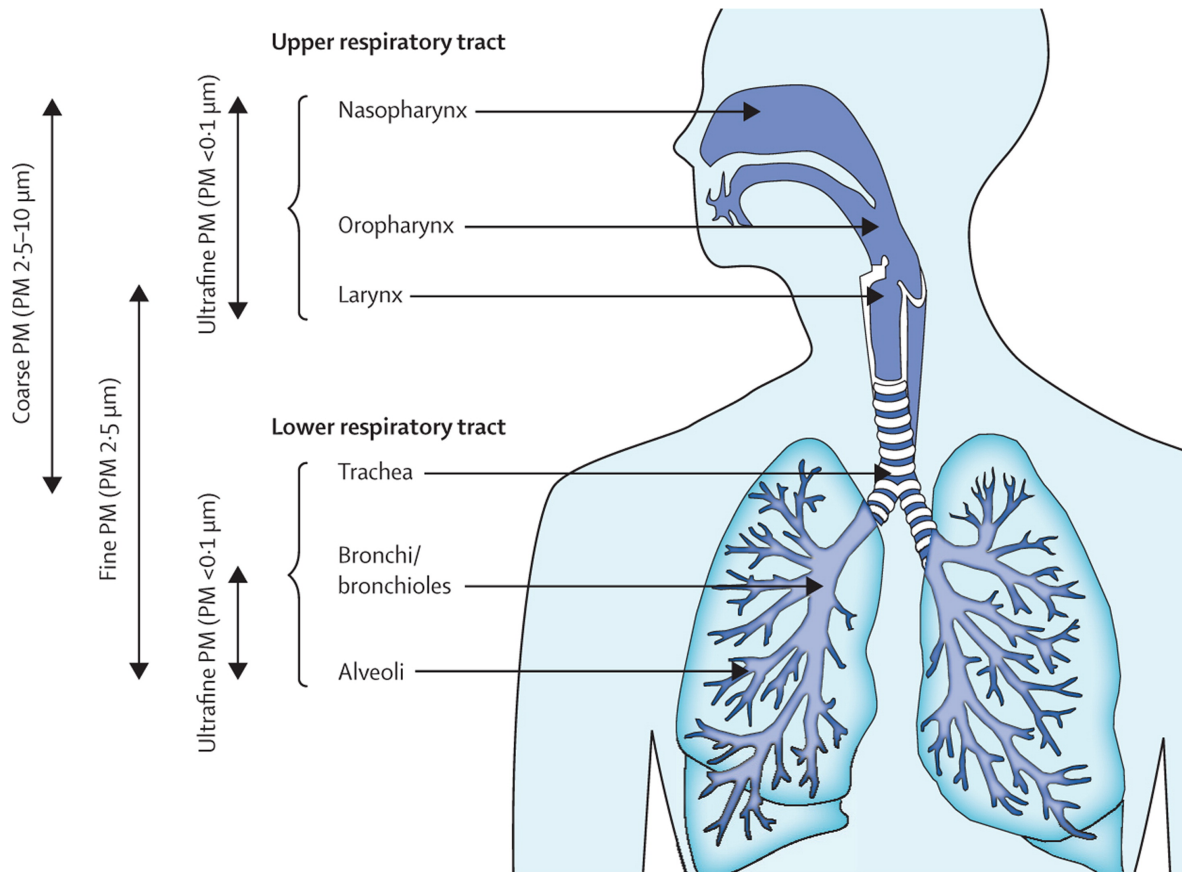
Figure 1-17: Diagram showing penetration of different PM size fractions into the respiratory tract (Source: Guarnieri & Balmes, 2014).

1.8.3.1 Short-term vs Long-term exposure

Health impacts can occur due to exposure over the short term (hours, days) or longer term (months, years). Strong evidence exists that short-term exposure to PM_{10} contributes to acute health outcomes like eye irritation, respiratory illness, exacerbation of existing conditions (e.g. asthma) and increased hospital admissions, but not to chronic conditions and mortality. These acute health impacts are more likely to affect more susceptible populations including those with pre-existing conditions, children and the elderly (Brook *et al.,* 2010; WHO, 2013). Pope and Dockery (2006)

conducted a critical review of epidemiological studies investigating the health effects of PM in order to help "connect the dots" between various studies with different methodologies. After an analysis of 16 studies that included results from meta-analyses of daily time-series exposure studies and multicity studies of short-term exposure, they concluded that only small effects on mortality are associated with short-term (daily) changes in PM concentrations. The analysis revealed an average increase of only 1% in mortality for every short-term increase of 10 ug/m^3 in PM$_{2.5}$. Their conclusion: it is unlikely that small elevations in PM exposure over periods of only a few days could be responsible for large increases in death (Pope & Dockery, 2006).

Long-term exposure to PM$_{2.5}$ poses the most significant risk to human health and is known to induce or accelerate the progress of chronic disease. Repeated exposures to air pollution over the long term thus not only directly cause disease, but may also increase susceptibly to disease (Pope & Dockery, 2006). Long-term exposure is associated with increased risk of lung cancer and cardiovascular-, cerebrovascular- and respiratory morbidity and mortality (Brook *et al.*, 2010).

Table 1-6: U.S. EPA determinations of causality between health impacts and short-and long-term exposure to PM.

Exposure	Size Fraction	Health Outcome	Causality Determination
Long-term	PM$_{2.5}$	Cardiovascular health impacts	Causal
		Mortality	Causal
		Respiratory health impacts	Likely to be causal
		Reproductive and developmental health impacts	Suggestive
		Cancer, mutagenicity and genotoxicity	Suggestive
Short-term	PM$_{2.5}$	Cardiovascular health impacts	Causal
		Mortality	Causal
		Respiratory Effects	Likely to be causal
Short-term	PM$_{10-2.5}$	Cardiovascular health impacts	Suggestive
		Respiratory health impacts	Suggestive
		Mortality	Suggestive

Source: (U.S. EPA, 2012).

The United States Environmental Protection Agency (U.S. EPA) conducted its own review of epidemiological studies in order to inform a review of their NAAQS for PM and reached similar conclusions as those discussed above (U.S. EPA, 2012). Their conclusions for the causal relationship between short- and long-term exposures for several health outcomes are summarised in Table 1-6.

1.8.3.2 Shape of the Concentration-Response Function for PM

The statistical cause and effect relationship between air pollution (cause) and specific health outcome of interest (effect) is represented by what is referred to as the concentration (or dose)-response function (CRF). CRFs are calculated by relating a specific health impact to a measure of pollution (while controlling for other factors), allowing an estimation of the role of the pollutant in causing the impact. Establishing this relationship allows us to then predict the improvement we can expect in the impact/outcome if we decrease the pollutant of concern by a certain amount. CRFs vary in shape and may be linear or non-linear and often contain thresholds, levels of exposure after which impacts increase drastically (OECD, 2003).
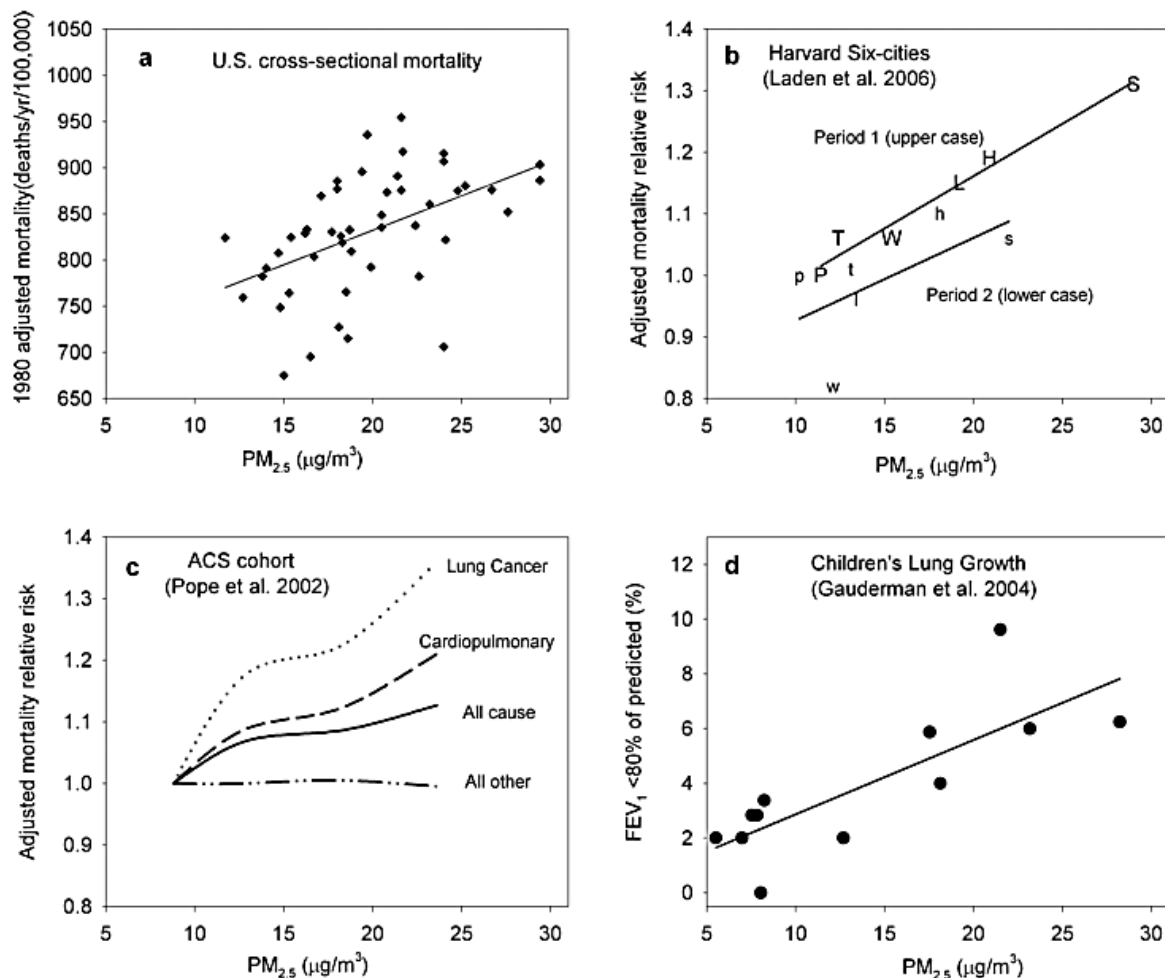
Figure 1-18: Comparison of Concentration-response functions estimated from various studies of long term exposure to PM2.5 (Source: Pope & Dockery, 2006:721).

Epidemiological evidence suggests that a well-definable "no-effects threshold" does not exist for exposure to PM on either the short- or long term. In their critical review, Pope and Dockery (2006:277) conclude that "the best empirical evidence suggests that, across the range of particulate pollution observed in most recent studies, the concentration-response relationship can reasonably

be modelled as linear". This means that, as exposure increases, so does the adverse health impacts associated with PM. Their summary of the CRFs estimated from various multicity time-series studies and long-term exposure studies are presented in Figures 1-18 and 1-19.
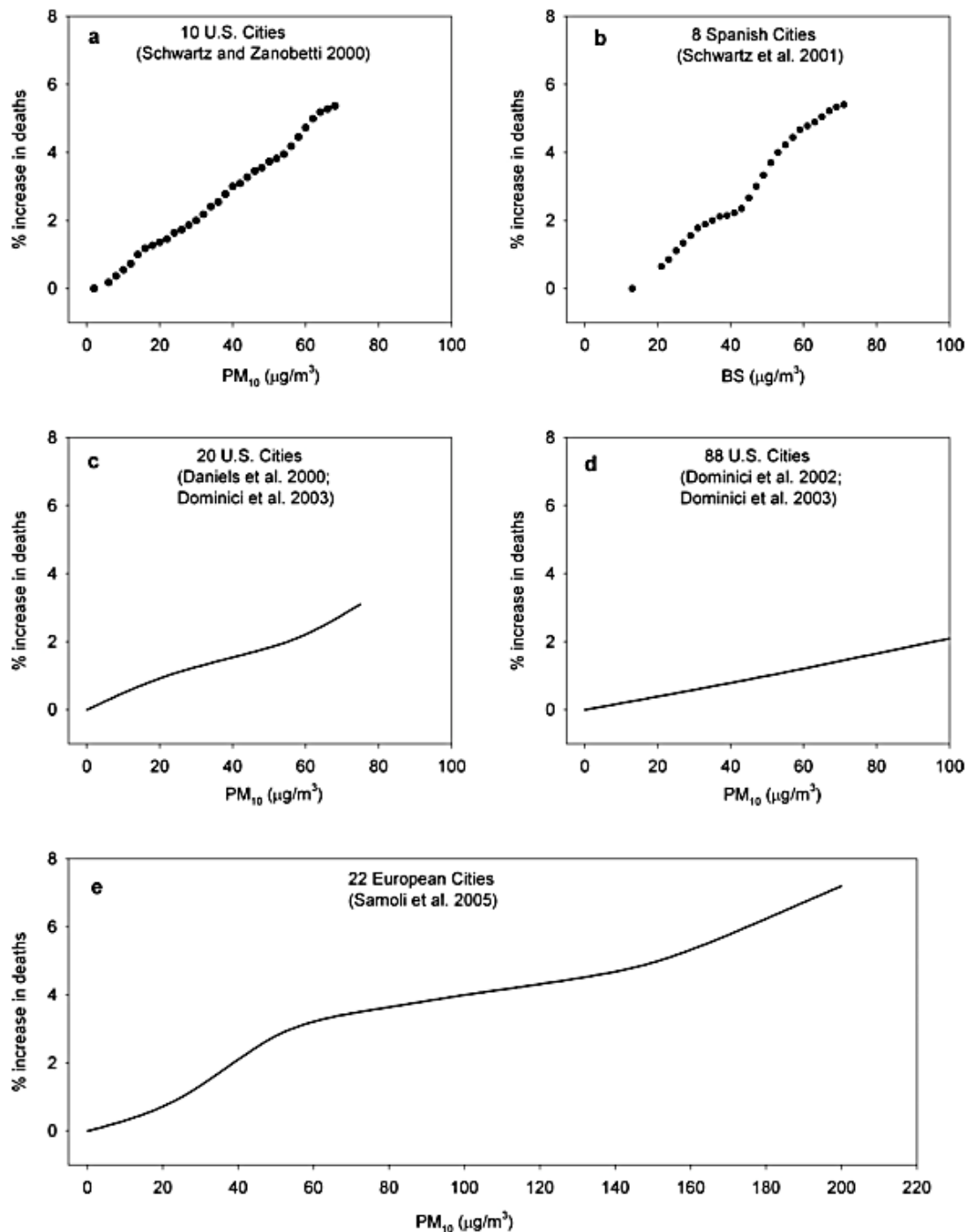
Figure 1-19: Comparison of Concentration-response functions estimated from various multicity daily time series mortality studies (Source: Pope & Dockery, 2006:720).

1.8.3.3   Pathophysiological pathways between air pollution and health impacts

Determining the exact pathway that links exposure to air pollution to specific morbidity and mortality outcomes remains elusive. It is likely that multiple pathways exist and that there are complex interactions and interdependencies amongst them (Figure 1-20) (Pope & Dockery, 2006).

For example, PM exposure is associated with the development and exacerbation of Chronic Obstructive Pulmonary Disease (COPD). The decline in lung function, systemic inflammation and oxidative stress associated with COPD in turn substantially contributes to cardiovascular morbidity and mortality (Van Eeden *et al.,* 2005). Pulmonary and systemic oxidative stress have also been linked to the initiation and acceleration of atherosclerosis (build-up of plaque in the arteries). Atherosclerosis in turn, increases risk of myocardial infarction (heart attack) and stroke. Evidence also exist that PM exposure results in altered immune system functioning and also affects cardiac autonomic function, leading to cardiac arrhythmia and cardiac arrests (Pope & Dockery, 2006).
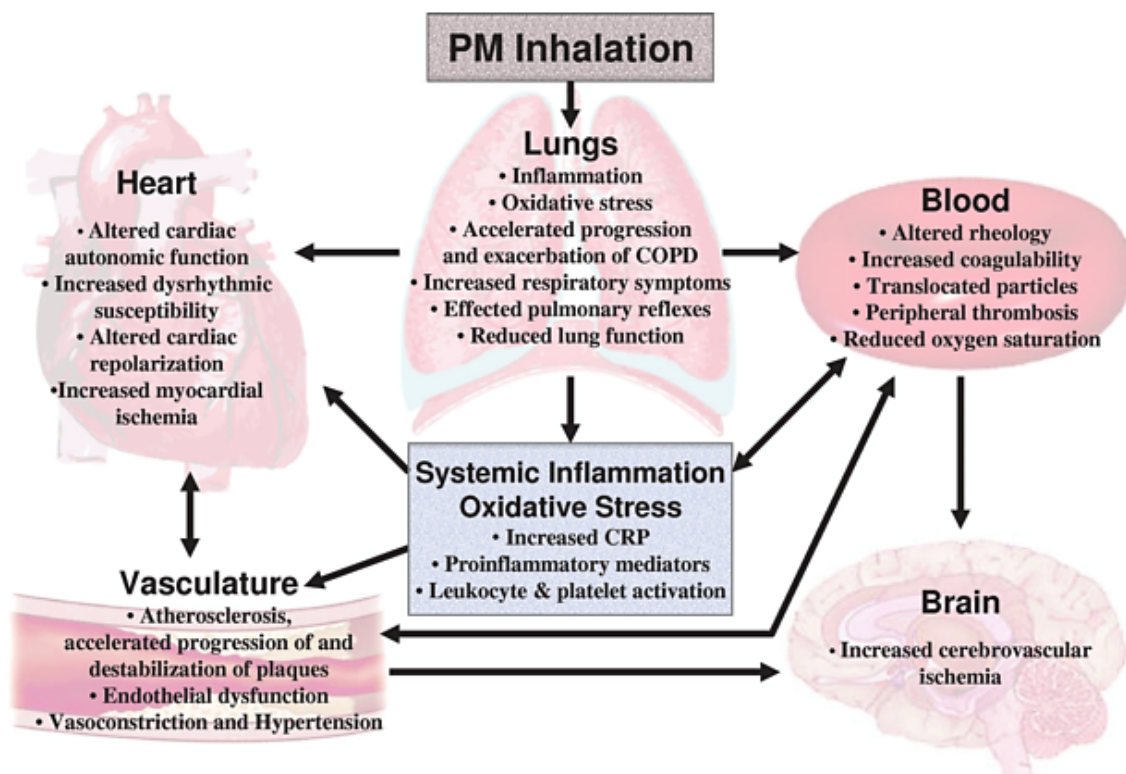
Figure 1-20: Potential pathophysiological pathways linking PM exposure to various health impacts (Source: Pope and Dockery, 2006:729).

Further discussions about the health impacts of air pollution on specific populations are provided in the introductory sections of the three manuscripts included in Chapters 3,4 and 5.

1.8.4   Assessing the health impacts of current or future air quality scenarios

Quantitative and qualitative data is needed to provide policy makers with information about the possible impacts of a policy, project or programme on air quality and human health. Health impact assessment (HIA) provides a means to extrapolate the findings from epidemiological studies to different populations and scenarios and provide information on the expected impacts on health due to current or future levels of air pollution (Ostro, 2006). The International Association for Impact Assessment (IAIA) defines Health impact assessment as *"a combination of procedures, methods and tools that systematically judges the potential, and sometimes unintended, effects of a policy, plan, programme or project on the health of a population and the distribution of those effects within the population"* (Quigley *et al.*, 2006:1).

HIA uses routine environmental, population and health data to relate air pollution concentrations to health impacts in a chosen population. The HIA process and data requirements are discussed in detail in Chapters 3 and 4. For reference, the main steps of HIA are illustrated by the diagram in Figure 1-21.
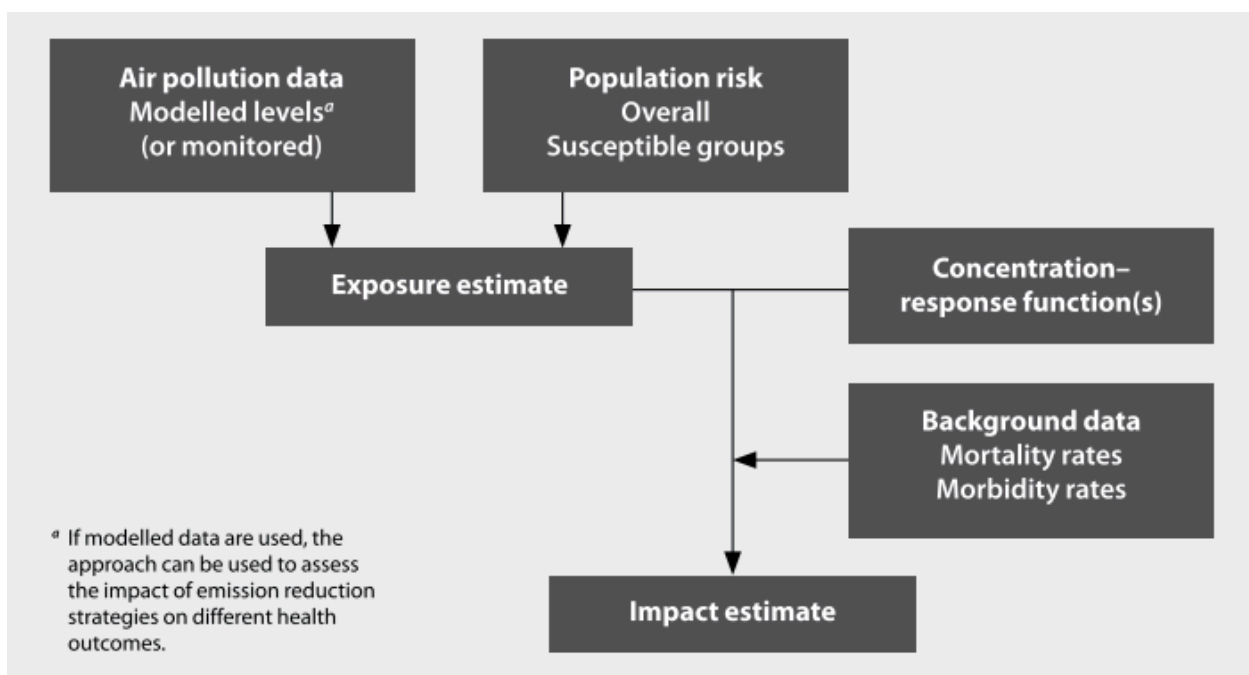
Figure 1-21: Schematic presentation of the main inputs required for Health Impact Assessment (Source: Ostro, 2006:157).

HIAs can be used to estimate the health impacts of various scenarios for example: "business as usual" scenarios where no air pollution controls are established, or "control" scenarios in order to estimate the impact that a certain policy or control measure would have on health in the exposed population. They can be conducted at the local, regional or global scale to help inform decision

making about policies and interventions that can prevent disease and to actively promote health (Pascal, 2011). Mathee and Wright (2014) recommend HIA as a tool to help protect public health in South Africa by using results to create "healthy policies" in other economic sectors such as housing, agriculture and transport. HIA can be used, for example, to protect farmers and consumers from excessive chemical exposure by establishing the health impacts of fertilisers and pesticides used to boost crop yields.

In the South African air quality context, HIAs conducted include: a study to estimate the contributions of specific sources to the health burden in the Vaal triangle (Scorgie *et al.*, 2003), another to estimate the impact of household cooking and fuel use on acute respiratory health of preschool children (Wichmann & Voyi, 2006) and a study by Terblanche *et al.* (1995) that estimated the impacts on respiratory health of three electrification scenarios in the low-income settlement of Sebokeng.

Various recent studies used HIA to estimate the impact of air pollution at the global the scale. The recently updated Global burden of disease (GBD) study was conducted to "help identify emerging threats to population health and opportunities for prevention" (GBD 2013 Risk Factors Collaborators, 2015:2287). Out of 79 identified global risk factors, air pollution ranked as the fifth most important risk factor for death and disease. They estimate that air pollution was responsible for 5.5 million deaths in 2013, with almost half of these deaths attributable to exposure to HAP in developing countries (GBD 2013 Risk Factors Collaborators, 2015). Feigin *et al.* (2016) used data from the GBD study to estimate the global burden of stroke and found air pollution to be a significant contributor to the global stroke burden, especially in developing countries. They estimate 29.2% stroke incidence to be attributable to air pollution. Both these studies recommend that air pollution, a modifiable risk factor, should be addressed in order to improve human health around the world.

HIAs conducted at the regional scale include Pascal *et al.* (2013), who assessed the public health impacts of urban pollution in 25 European cities as part of the APHEKOM project and Fann *et al.* (2012) who estimated the national public health burden associated with $PM_{2.5}$ and Ozone in the United States. Norman *et al.* (2007) estimated the burden of disease attributable to urban air pollution in South Africa for the year 2000. Their findings report that AAP in urban areas contributed to 3.7% percent of mortality from cardiopulmonary disease, 5.1% of mortality from cancers of the trachea, bronchus and lung and 1.1% of mortality from acute respiratory infections in children under five. They conclude that the public health impacts of air pollution remain under recognised in South Africa and that fossil fuel combustion emissions and traffic-related air pollution should be reduced to protect public health. Altieri and Keen (2016) used the U.S. EPA Environmental Benefits Mapping Program (BenMAP) to estimate the health impacts of two scenarios: reducing NO_2 concentrations by 15% and reducing PM_{10} concentrations to below the WHO recommended 24-hr standard for all

municipalities in South Africa. Their results showed that improvements in air quality would lead to significant reductions in premature mortalities, with the largest benefits in densely populated urban areas.

Local scale HIA is often conducted at the city or community level, for example Voorhees *et al.* (2014) investigated the public health benefits of reduced air pollution in Shanghai, China; Broome *et al.* (2015) estimated the health benefits of improved air quality in Sydney, Australia and Keen and Altieri (2016) assessed the health benefits of attaining the NAAQS for SO_2 and PM_{10} in the city of Cape town.

It is evident that HIA is a tool that is valuable in assessing the impacts of various scenarios within the air quality context. Chapters 3, 4 and 5 discuss the considerations and inputs required to estimate the benefits of interventions to reduce residential solid fuel burning in more detail.

1.9   Economic impacts of air pollution

It is evident from the definitions and discussions given above that air pollution has many harmful impacts on infrastructure as well as human, animal and ecosystem health. All these impacts have economic consequences that are predicted to significantly impact long term global economic growth, if not addressed promptly (OECD, 2016).

Hutton (2011) estimated the global damage costs of air pollution from 1900 to 2010 to be US$ 30 trillion, losses equivalent to US$ 430 for every person alive at that time (5.6% of the Gross World Product). Outdoor and Indoor air pollution were responsible for almost equal amounts of the estimated damage costs, with two thirds of these damages affecting the populations of developing countries. Ten air pollution related impacts were included in this analysis: Human health impacts (mortality and morbidity), aesthetics (visibility), buildings/non-organic materials, agricultural impacts, climate change, ecosystems/biodiversity, water resources for human use, acid rain and other socio-economic impacts (time use). Health related costs were found to account for 85% of total air pollution related damages in 2010. As the focus of this study is on the health impacts of air pollution, all further discussions of economic valuations and impacts will be made in this context.

Costs related specifically to the health impacts of air pollution are generally divided into three categories: direct costs, indirect costs and intangible costs (Chanel, 2011). Direct costs are further divided into medical costs (direct costs of medical resources used) and non-medical costs (directly related to the health impact, but not medical in nature). Indirect costs include costs associated with the loss of various resources and intangible costs refer to costs that apply not only to the person affected, but also to their friends and family (Chanel, 2011; Hutton *et al.*, 2007; OECD, 2016). Refer to Table 1-7 for examples of these costs.

Table 1-7: Health related costs of air pollution

Direct medical costs	Direct non-medical costs	Indirect costs	Intangible costs
• Consultation fees • Medication • In- and out-patient hospitalisation • Emergency room visits • Cost of rehabilitation after illness	• Cost of social services and support (e.g. home help) • Home modifications • Transportation costs	• Loss of productive work by patient • Loss of productive work by family and friends of patient • Loss of productive work due to early retirement and/or premature death	• Grief, fear, pain unhappiness (for patient and their family or friends) • Loss of well-being • Loss of quality of life

Source: (Chanel, 2011:8).

1.9.1 Economic valuation of air pollution related health impacts

The economic value of the health-related impacts of air pollution are most commonly calculated in terms of cost of premature death (mortality); medical cost of illness (morbidity) and loss of productivity due to illness.

Economic valuations can be conducted to estimate the costs associated with many air pollution scenarios. Valuation studies are used to estimate costs associated with present levels of air pollution or to project the economic impacts that a certain scenario or policy might have in the future (for improved or declining air quality). These methods are applicable to scenarios at all scales, from the global to community (Hutton, 2011; OECD, 2016b, 2011; U.S. EPA, 2016). According to Hutton and Rehfuess (2006), economic valuation "enables explicit and quantitative comparisons of the efficiency of interventions using a simple-to-interpret summary efficiency measure – cost per impact achieved – as the common outcome measure".

Results of economic evaluations can be a powerful tool to aid decision making in various ways. At the project level, it can inform choices between alternatives considered for large scale implementation, and for governments, it aids policy-making, planning and decision-making. It also serves as a measure to assess the social impacts of interventions and their spatial distribution (Hutton & Rehfuess, 2006).

The two main types of economic valuations used to quantify and compare the results of interventions are cost-benefit analyses (CBA) and cost-effectiveness analyses (CEA). Cost-utility analyses (CUA) are a subtype of CEA measuring health outcomes in generic terms, allowing for better comparison

between interventions addressing different health outcomes. CEAs are most commonly used to measure the benefits of health interventions in health units, whilst CBAs value all outcomes in terms of monetary value (Hutton & Rehfuess, 2006).

Mehta and Shahpar (2004) conducted a cost-effectiveness analysis (CEA) to assess three intervention scenarios aimed at reducing residential solid fuel burning in five regions around the globe. They assessed the health benefits associated with a) access to cleaner fuels, b) access to improved stoves and c) providing half their study population with access to cleaner fuels and the other half with improved stoves. Their analysis concluded that even though access to cleaner fuels yielded higher health benefits, access to improved stoves was the most cost-effective intervention in terms of improving health per unit of investment.

Voorhees *et al.* (2014) estimated the economic benefits of attaining China's Class II air quality standards in the city of Shanghai. The economic benefit associated with avoided premature mortality was estimated to be between 170 million yuan to 1200 million yuan and that of avoided hospital admissions between 20 to 43 million yuan (where 1US\$ = 4.2 yuan Purchasing Power Parity (PPP) adjusted).

When comparing the benefits and costs of air pollution controls implemented in terms of the United States' Clean Air Act of 1990, the U.S. EPA (2011) concluded that the benefits of improved air quality would vastly exceed the costs (to both the private and public sectors) needed to comply with legislation. As seen in Figure 1-22, the annual costs of efforts to meet the requirements of the act are estimated to reach an annual value of around US\$ 65 billion in 2020, whilst the associated benefits of improved health, improved economic welfare and better environmental conditions are estimated to be almost US\$ 2 trillion for the same period.

The OECD (2016) predicted that global air pollution related health care costs will increase from US\$ 21 billion in 2015 to US\$ 176 billion in 2060. They further predict losses of productive working days to increase from the current 1.2 billion days to 3.7 billion days in in 2060.

In South Africa, Leiman *et al.* (2007) conducted a CBA on a range of policy and technological interventions intended to reduce air pollution related health costs in densely populated urban areas, and found that the most efficient interventions would be at the household level. They found that most of the proposed industrial interventions included in the study failed to show a cost benefit. In this case, the economic evaluation of health impacts revealed that in the South African context, many industrial controls were not yet justifiable economically and that household air pollution should be the main target of intervention efforts. Based on their findings the five most economically viable interventions (based on improved health outcomes) are:

(1)   Housing insulation in 20% of all fuel burning households;

(2)   Stove maintenance and replacement in 20% of all households;

(3)   Electrification of dirty fuel burning households;

(4)   Top down ignition methods in all conurbations;

(5)   Department of Minerals and Energy strategy for all new vehicles to comply with Euro 2 standards.
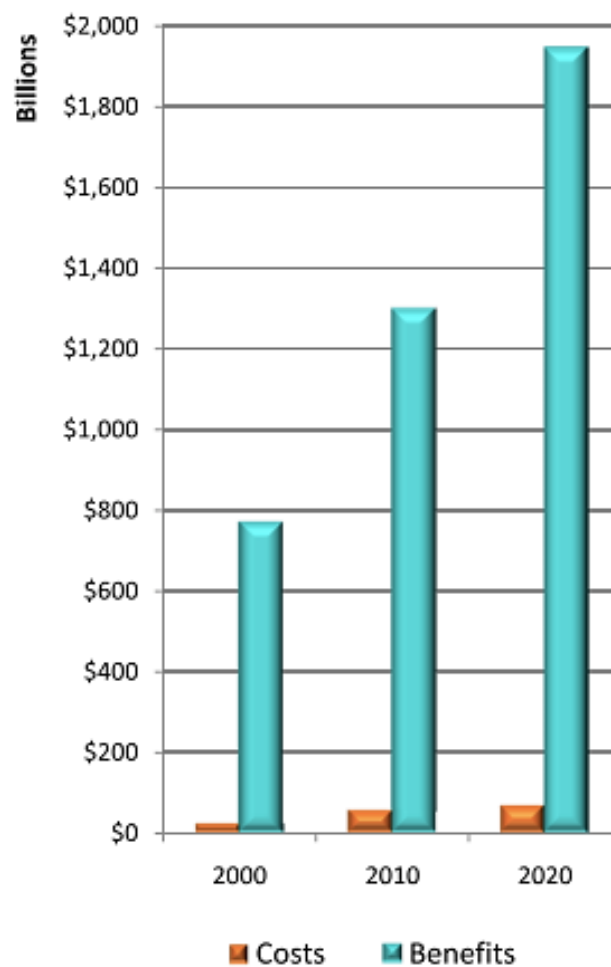
Figure 1-22: The costs and benefits of meeting requirements of the U.S. Clean Air Act of 1990 (Source: U.S. EPA, 2011:3).

This study will only focus on the economic benefits of reduced premature mortality, as no other health outcomes were analysed.

1.9.1.1 Valuating the economic benefits of avoided premature mortality

Valuating the health impact of air quality management policies and interventions can help compare associated costs and expenditures to associated benefits. This value is determined by the value that we attach to health and safety compared to the value attached to other goods. To estimate the value of avoided mortality, we need to attach a value to the small reductions in risk that occur in a population when air quality improves (Abelson, 2008).This value is referred to as the Value of a Statistical Life (VSL).

The U.S. EPA (2016:4) defines the VSL as "*an aggregation of individuals' willingness to pay for a small reduction in each of their annual mortality risks. When summed over a large number of individuals such that there is one fewer expected death in that population over one year, the aggregate willingness to pay is referred to as the VSL*". The term is often misinterpreted as a monetary measure of avoiding certain death for a single individual and as such, the U.S.EPA is considering replacing the often misunderstood VSL with an alternative term in its future reporting. New terms under consideration include Value of Mortality Risk (VMR) and Value of Risk Reductions (VRR) as they more accurately portray the risk reductions associated with environmental policies (U.S. EPA, 2016).

VSL estimates are typically derived from stated preference studies where respondents themselves report their willingness to pay for a change in mortality risk, or from labour market studies where hedonic techniques are used to derive the value of small reductions in risk. No such studies are available for South Africa and thus the U.S. EPA standard VSL was used. This approach was also followed by Leiman *et al.*, (2007) and detailed descriptions of how the VSL was calculated can be found in Chapters 4 and 5.

Using the VSL as valuation estimate is not without controversy. Ackerman and Heinzerling (2002:16) criticize the practice of economic valuation by stating that, "on a philosophical level, human life may belong in the category of things that are too valuable to buy and sell". They also contend that it is impossible to aggregate the amount that certain individuals are willing to pay into a figure that prescribes what society should pay to protect a human life. This is due to the fact that "risk of death is not the same as death itself" and that it is impossible to reasonably compare all risks to one another. They are thus of the opinion that most economic valuation techniques, including the use of the VSL, excludes questions of fairness and morality. In their opinion, monetising benefits too often trivialise future impacts and the irreversibility of some environmental problems. Despite criticism and flaws in existing methodologies, the economic valuation of health benefits, (also called monetised benefits) is the most common way used to attach an economic value on improved environmental conditions and health.

CHAPTER 2

DATA AND METHODS

2.1 Introduction

This chapter provides a summary of the data used and methods followed to estimate the health and economic benefits of thermal insulation as an air pollution intervention measure in low-income settlements on the Highveld. For this study, a health impact assessment (HIA) was conducted to estimate the number and economic value of avoided premature mortalities that could be expected through reductions in air pollution in low-income settlements in the study area. Since this dissertation document follows the article format, the data and methods used to obtain the objectives of this study are also explained within each manuscript and where appropriate, relevant sections are referenced.

2.2 Inputs required to conduct HIA in the South African context

The first objective of this study, to investigate and evaluate the relevant socio-economic and physical variables needed to conduct the health and economic impact assessment, is addressed in Manuscript 1 (Chapter 3) titled *"Health impact assessment of interventions to reduce residential solid fuel burning: challenges and considerations.",* and Manuscript 2 titled *"The health and economic benefits of thermal insulation interventions to improve air quality in a South African township"*

The first paper investigated and evaluated the relevant socio-economic and physical variables needed to conduct the health and economic benefit assessment, and takes the form of a review. Firstly, a thorough literature review was conducted to investigate the methodologies, considerations and needed inputs to conduct the health and economic impact assessment. Sources consulted include international best practice guidelines for health and economic impact assessment, epidemiological literature, air quality studies, health impact assessments conducted both locally and internationally and relevant South African legislation.

After the relevant physical and socio-economic variables needed as inputs for the analysis were identified, a search was conducted on the Statistics South Africa 2011 Census database to evaluate the availability and suitability of population and mortality data for HIA in the South African context.

The South African Air Quality Information System database (SAAQIS) was used to evaluate the availability and suitability of monitored air quality data in the study area. Several economic

databases, including the World Bank Open DataBank, the International Monetary Fund World Economic Outlook Database and economic indicators from Statistics South Africa were consulted.

Information and conclusions reached in this paper helped inform choices regarding the data and methodology used for the main analysis.

In order to test the viability of using pre-designed HIA tools developed for use in other countries in the South African context, we used the Environmental Benefits and Mapping tool (BenMAP) developed by the U.S EPA to conduct a health and economic impact assessment of the community scale pilot offset project used as the control scenario in our main analysis. Findings from this paper informed methodological decisions for the regional scale HIA discussed under objective 3.

A detailed description of the project site and data and methods used for this analysis is provided in Manuscript 2, titled *"The health and economic benefits of thermal insulation interventions to improve air quality in a South African township".* As the scope of this study does not include a local scale HIA the discussions about this project are limited to the air quality data used to achieve objective 2 of this study.

2.3 Quantification of the spatial variation of pre- and post-intervention PM$_{2.5}$ concentrations over the Highveld

In order to estimate the health impacts of improvements in air quality, two sets of air quality data are needed: Baseline (pre-intervention) concentrations and Control (post-intervention) concentrations. The control scenario in a modelling study "is a sensitivity scenario in which emissions from one or more source sectors are changed (increased or decreased) from a given baseline scenario" (Abt Associates Inc., 2012:2-4) The control scenario generally represents air quality levels after a new policy has been implemented. Baseline conditions are used as a reference scenario against which to compare the intervention or control scenario. In this context, the control scenario refers to PM$_{2.5}$ concentrations after the installation of thermal insulation in existing houses.

2.3.1 Pre-intervention (baseline) PM$_{2.5}$ concentrations

Baseline scenarios can be derived from model based estimates or monitored air quality data. To reduce the influence of atypical years or seasons, it is recommended that data used to create the baseline scenario should be based on several recent years of complete data (Ostro, 2006).

Various methods were considered to create a representative baseline scenario:

1. The use of a refined dispersion model like CALPUFF. The benefits of using a model like CALPUFF include its consistent spatial distribution of the variable of interest and the ability to model basic chemical processes like basic secondary particle generation, for example. Detailed emissions

inventories and meteorological data are needed to run the model, however. This, along with the fact that it was not designed for near ground, high resolution modelling lead to the decision to not use CALPUFF to create the baseline scenario.

2. The use of a comprehensive air quality model like CAMx. Similar to CALPUFF, this model offers consistent spatial distribution of the variable of interest along with more advanced chemistry options (e.g. secondary particle generation). This model also requires detailed emission inventories and meteorological data and was not designed for near ground, high resolution areas. The lack of reliable emission data severely limits the application and evaluation of models to estimate ground level PM. The use of CAMx was thus also excluded.

3. The use of remotely sensed air quality data and Aerosol optical depth (AOD) have been shown by Brauer *et al.* (2013) to provide more spatially resolved estimates of ambient PM concentrations. AOD also frequently correlates with monitored ground observations of particulate concentrations and has been suggested as an appropriate proxy for ground level PM in several regions. While remote sensing algorithms to quantify ground level PM have improved, the ability to detect ambient PM in low-income areas of South Africa has been shown to be poor (Hersey *et al.,* 2015).

4. The use of monitoring data to estimate ambient concentrations. This study requires annual mean concentrations. As mentioned above, most modelling efforts currently do not provide enough certainty for emissions that contribute to ambient air quality in low-income settlements. For HIA in low-income areas, the high spatial- and low temporal variability need to be presented as accurately as possible as these areas house a significant portion of South African society. Areas just outside low-income areas typically show less variability over space on the annual time frame (Burger and Piketh, 2016). The steep population gradients so typical of South African urban areas, also require spatially resolved air quality data to ensure accurate exposure estimates (Cairncross, 2016).

Monitoring data is the only reliable way to do this, despite the limitations of limited monitoring sites and high spatial variability in the study area. For these reasons, a land use type ordinary least squares regression, using available monitoring data was chosen to model baseline concentrations for this study.

2.3.1.1 Data collection and management

Monitoring data for PM_{10} were obtained from the South African Air Weather Service via the South African Air Quality Information System (SAAQIS). Data were requested for all monitoring stations in the study area for all years that data were available for each respective station.

The raw datasets were merged and processed into a final dataset. An automated quality control was performed and problematic values were flagged. Flagged data was inspected manually to determine

the validity of the potential problems. The data for any problem periods were set to missing. Data retention after quality control was generally good. At only two stations data recovery was below 80% (Alexandra, 45% and Diepsloot, 79%). 17 of the 30 monitor stations used in this study were located in densely populated low-income settlements. Thus 56% of the monitoring stations used to estimate exposure levels in low-income settlements could be considered very representative of the average concentrations and exposure levels in the study population. Figure 2-1 shows the location of monitoring stations used in this study and Table 2-1 provides a description of the land use type along with the periods for which data were available, the percentage of data available and percentage data retention after quality control (QC).

Data from the 2011 Census were used to deploy the model. Enumeration Areas (EAs) (also called small area levels) were chosen for the scale of analysis as they are the smallest geographical areas where detailed housing and household related statistics are recorded during a census. Conducting the analysis at this small scale should better represent the spatial and socio-economic factors that influence exposure in densely populated low-income communities (Wright & Diab, 2011).
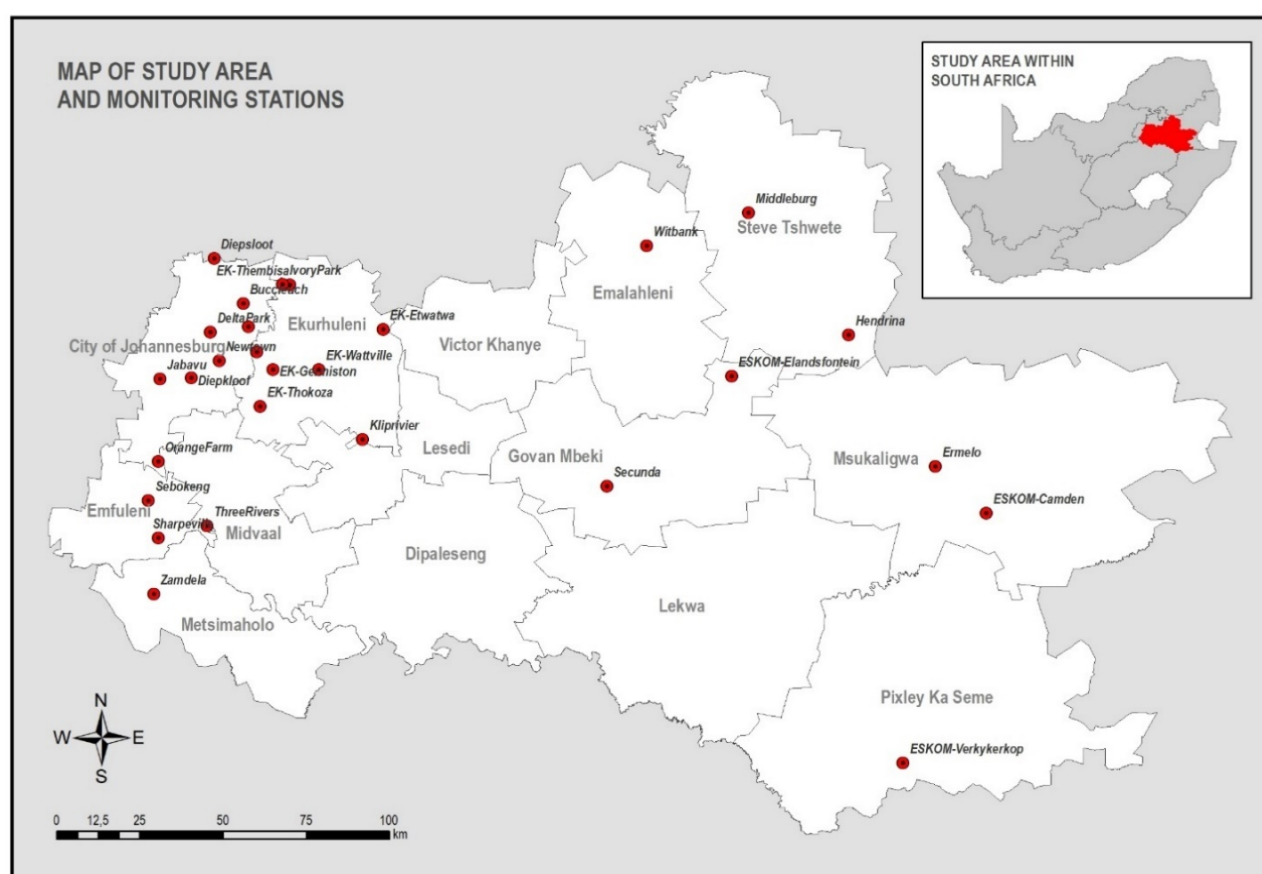
Figure 2-1: Locations of monitoring stations used to estimate baseline PM2.5 concentrations in the study area.

To avoid overfitting and covariance during the regression, only three independent variables considered to be indictors of poor HAP and higher population exposure were used: 1) the percentage of households using dirty fuels for cooking, heating or lighting in each EA; 2) the percentage of households living in informal housing in each EA and 3) the population density in each EA. Average annual PM_{10} concentrations were used as the independent variable.

The model was trained using the variables obtained from the different sources within a 250m radius of each of the available monitoring stations and the EA layer of the 2011 census data was used to deploy the model. After model deployment, a PM concentration was assigned to the centroid of each EA, providing a better spatially resolved estimate of population exposure in each area (Figure 2-1.)

Modelled PM_{10} concentrations were converted to $PM_{2.5}$ using a conversion factor of 0.5. This conversion factor is recommended for use in urban areas of developing countries by the WHO (2006). This rate was also assumed by Norman et al. (2007) in areas where no monitored data were available to calculate an actual rate.
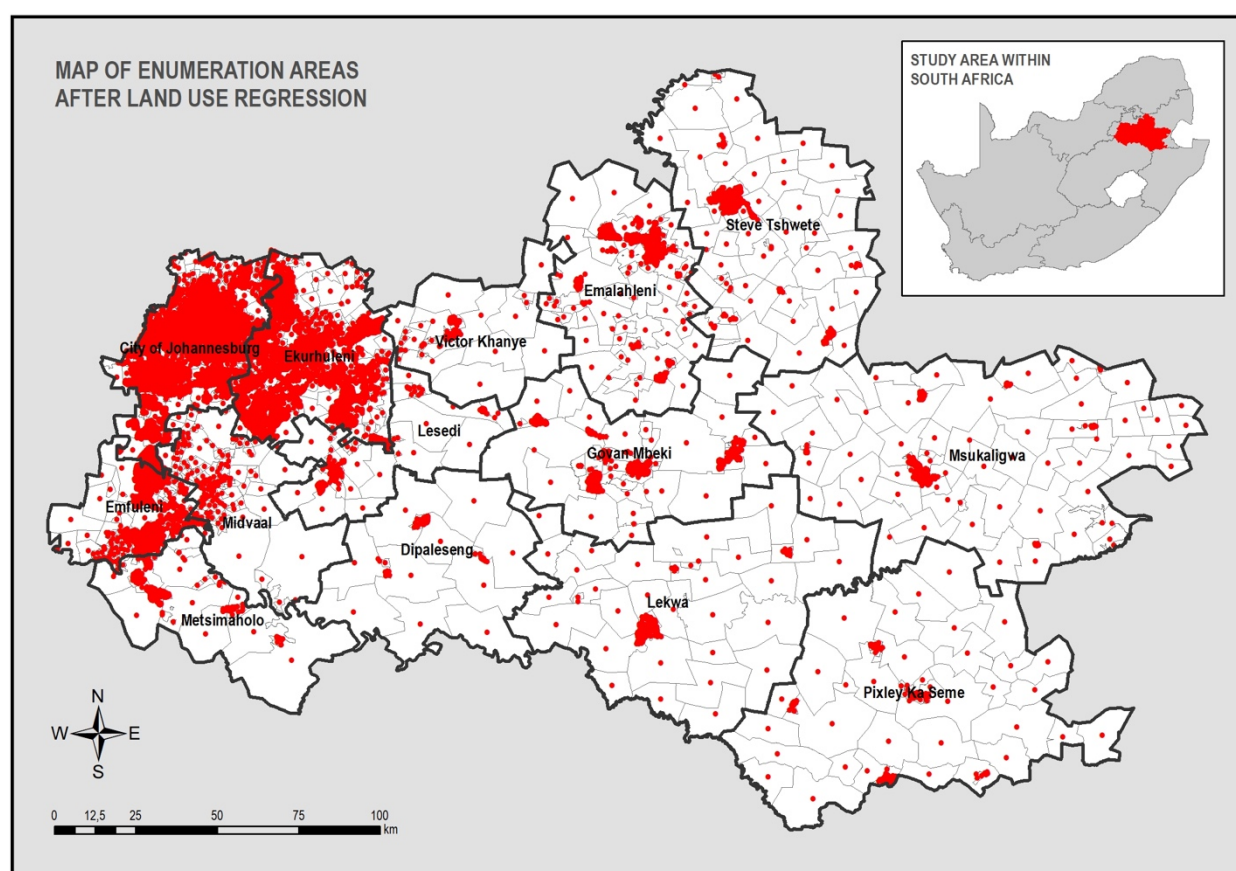
Figure 2-2: Map of study area after land use regression.

A description of the data used, quality control performed and methods followed to quantify the spatial variation in pre- and post-intervention $PM_{2.5}$ concentrations in the study area is provided in Chapter 4 under section 4.3.1 – Air Quality Data in the manuscript titled *"Estimating the regional health and economic benefits of an intervention to reduce residential solid fuel burning"*

Table 2-1: Monitor stations used to model pre-intervention $PM_{2.5}$ concentrations.

Monitor Site	Land use type	Data % available	Data % after QC	Number of days	Start date	End date
Newtown	CBD	67	99	2440	2004-07-31	2012-09-30
Alexandra	High density low-income	31	45	772	2004-01-01	2010-10-31
Diepkloof	High density low-income	80	95	2718	2007-02-05	2012-09-30
Diepsloot	High density low-income	41	79	272	2009-03-24	2012-09-30
Ermelo	High density low-income	90	98	2526	2008-09-01	2012-09-30
Etwatwa	High density low-income	87	98	448	2011-05-03	2012-09-30
Hendrina	High density low-income	66	99	1857	2008-09-01	2012-09-30
Ivory Park	High density low-income	43	89	432	2009-07-27	2012-09-30
Jabavu	High density low-income	74	100	2161	2004-07-14	2012-09-30
Mokopane	High density low-income	87	100	932	2012-09-01	2012-09-30
OrangeFarm	High density low-income	61	92	2273	2004-05-14	2012-09-30
Sebokeng	High density low-income	79	97	2611	2007-02-21	2012-09-30
Secunda	High density low-income	77	94	2140	2008-09-01	2012-09-30
Sharpeville	High density low-income	87	100	2859	2007-05-17	2012-09-30
Thembisa	High density low-income	81	100	519	2011-01-01	2012-09-30
Thokoza	High density low-income	76	100	459	2011-01-05	2012-09-30
Wattville	High density low-income	90	100	439	2011-06-01	2012-09-30
Zamdela	High density low-income	64	95	2083	2007-05-17	2012-09-30
DeltaPark	Low density residential	64	88	1647	2004-07-31	2012-09-30
Germiston	Low density residential	80	100	489	2011-01-01	2012-09-30
Kliprivier	Low density residential	82	92	2747	2007-02-09	2012-09-30
Lephalale	Low density residential	57	95	623	2011-01-01	2012-09-30
Middleburg	Low density residential	82	100	2487	2008-01-01	2012-09-30
Thabazimbi	Low density residential	60	100	807	2012-10-01	2012-09-30
Witbank	Low density residential	87	100	2438	2008-09-01	2012-09-30
Camden	Power station	81	100	885	2011-01-01	2012-09-30
Verkykerkop	Rural	94	100	629	2012-02-29	2012-09-30
Bedfordview	Urban Traffic	90	100	382	2011-08-01	2012-09-30
Buccleuch	Urban Traffic	62	95	2251	2004-07-31	2012-09-30

2.3.2 Post-intervention PM$_{2.5}$ concentrations

In order to most accurately represent the context of this study, we used the findings from a pilot air quality offset programme implemented in the low-income settlement of KwaDela, in the Msukaligwa local municipality in the study area, as our control value. This study is described in detail in Manuscript 2 titled *"The health and economic benefits of thermal insulation interventions to improve air quality in a South African township".* The discussion below will provide a brief description of the project and discuss the data and methods used to calculate the control value.

KwaDela was chosen as the project site because of its population characteristics, along with its geographic location far from industrial and other urban sources, small population size (total population of 3786) and high levels of dependence on solid fuel burning for cooking and space heating. Figure 2-3 (a) indicates the location of KwaDela on the Highveld.

The project involved a pre-intervention sampling campaign in the cold and warm seasons of 2013-2014, followed by retrofitting 505 houses in the settlement with thermal insulation from February to June 2014. After implementation, a sampling campaign was conducted in the cold and warm months of 2014 and early 2015, in order to establish post-intervention PM concentrations.

PM$_{2.5}$ was measured using a Met-One E-bam sampler deployed in the community during two pre-intervention and two post-intervention sampling campaigns. Figure 2-3(b) indicates the central location of the ambient sampling station in the community (29.664, -26.463).
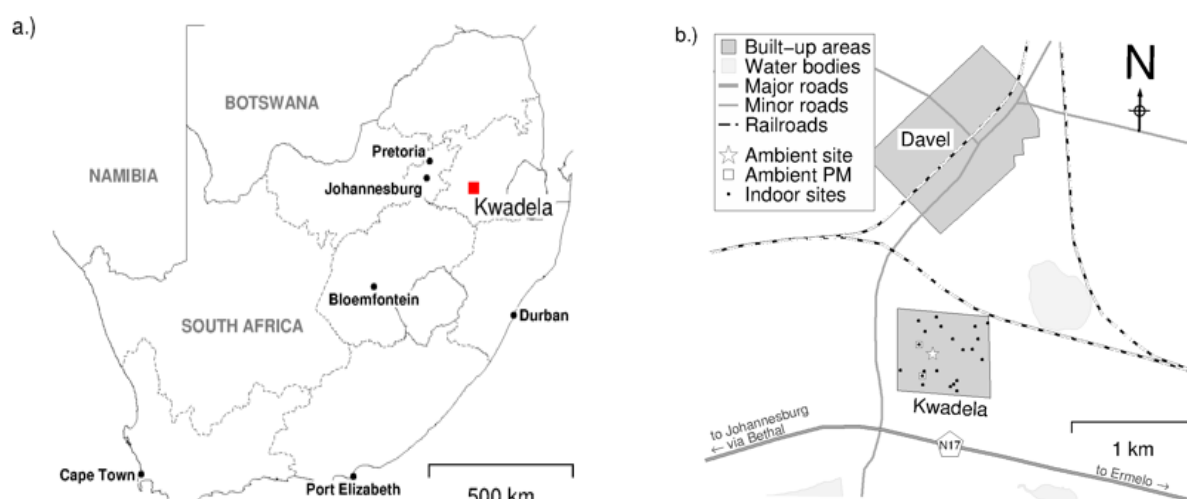
Figure 2-3: a) Location of KwaDela on the Highveld and b) Expanded view of the area surrounding KwaDela and location of sampling sites

Table 2-2: Pre-and post-intervention PM$_{2.5}$ sampling results for KwaDela

Sampling Period	Count	Mean	S.D.	Min.	50%	99%	Max	Data Retention
Winter 2013	63	35	12	12	35	82	89	78%
Winter 2014	69	30	9	12	29	50	50	52%
Summer 2014	47	20	14	1	19	60	68	91%
Summer 2015	62	18	4	11	18	32	35	96%

The monitoring site was visited every 2 weeks. Quality assurance was conducted by flagging all time periods as missing where instrument malfunctions were logged during the visits. Automatic checks, including buddy checks, typical concentrations for similar areas, and stuck values, were performed. Suspicious values were flagged and data was inspected manually to determine the validity of the potential problems. The data for any problem periods were set to missing. The most common problem was the mechanical failure of the filter tape advancement. The data for any problem periods were set to missing. Data retention for both sampling campaigns are shown in Table 2-2.

Table 2-3: Percentage of EAs identified for inclusion in the regional Health Impact Assessment by municipality

Municipality	Total EAs per municipality	% of EAs identified for inclusion in HIA
City of Johannesburg	5 800	5
Dipaleseng	76	76
Ekurhuleni	4 610	23
Emalahleni	457	52
Emfuleni	1 136	10
Govan Mbeki	455	53
Lekwa	194	65
Lesedi	187	54
Metsimaholo	260	29
Midvaal	184	37
Msukaligwa	259	83
Pixley Ka Seme	132	92
Steve Tshwete	458	52
Victor Khanye	122	80

Post intervention sampling revealed a small observable PM$_{2.5}$ reduction during peak heating hours in the cold months, but almost no reduction in warmer months. Significant reductions were observed between maximum daily averages (mostly on coldest says). A comparison of pre- and post-intervention measurements for both the warm and cold season sampling campaigns is summarized in Table 2-2.
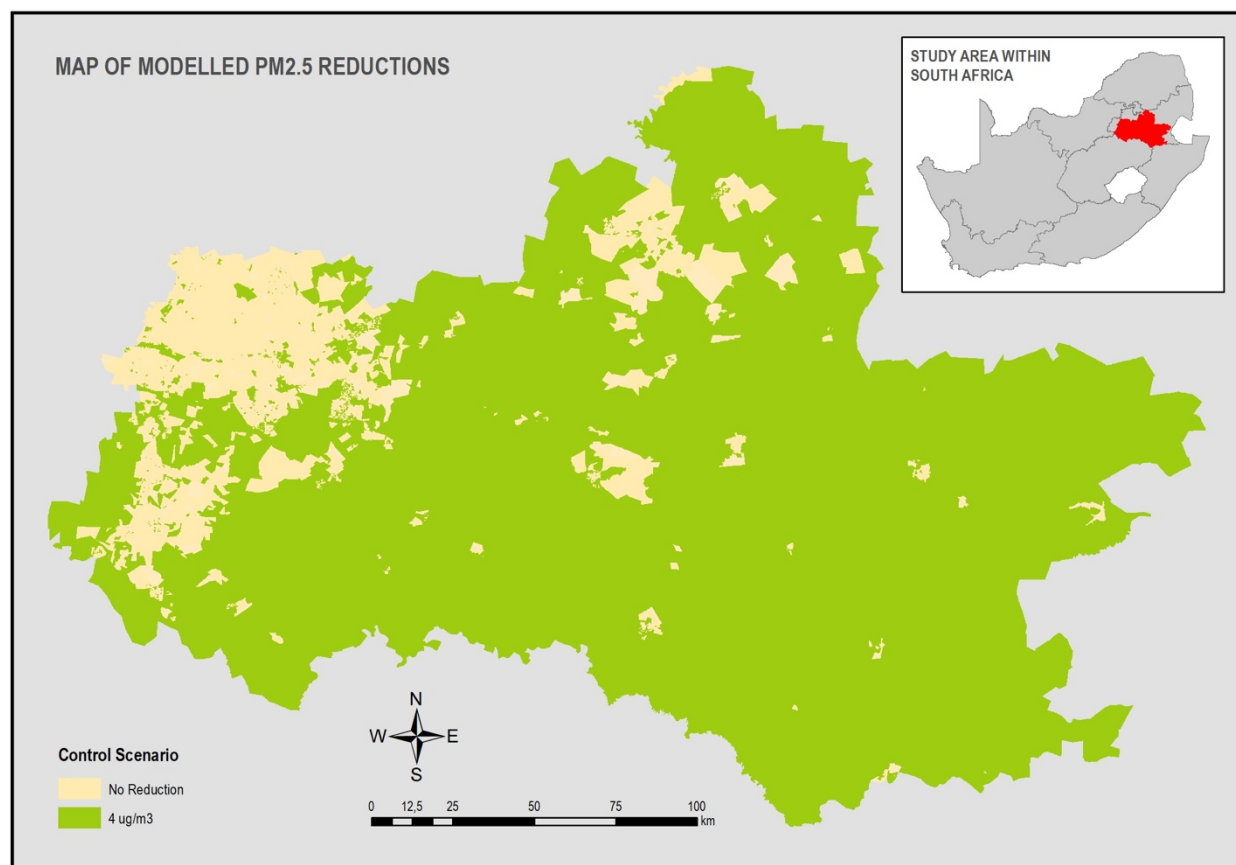
Figure 2-4: Map of areas identified for inclusion in the Health Impact Assessment.

The standard deviation of PM2.5 in KwaDela was on the same order of magnitude as the mean. This large variability would make it difficult to detect relatively small decreases due to planned interventions. The effect size is a common measure of the difference between two means. Cohen's (1988) definition of effect size (the difference between the two means as a fraction with standard deviation of the sampled data) was used to determine the effect size of the intervention. He defined effect size as small (d=0.2), medium (d=0.5) and large (d=0.8) and suggested that small and medium effects will be difficult to detect in the natural environment. In this case, effect size (d-value) represents the difference between the two means (4 μg/m^3) and was used to estimate the effect the intervention had on the ambient air quality in KwaDela. For this campaign, the difference did not

obtain statistical significance (*d*=0.6) and therefore the difference between the two means (4 μg/m^3) was used as the control value.

To create the post-intervention air quality dataset, the control value of a 4 μgm^3 reduction in mean PM$_{2.5}$ was applied to all EAs where more than 10% of households reported using dirty fuels as an energy source. PM$_{2.5}$ concentrations in areas where less than 10% of households reported using dirty fuels were left unchanged, as interventions would not be implemented in such areas.

Δ Values used in the control dataset were thus entered as either 0μgm^3 or 4 μgm^3. Table 2-3 shows the percentage of EAs identified for inclusion in the final analysis by municipality and Figure 2-4 their spatial distribution.

2.4 Determine the size and spatial distribution of health and economic benefits associated with reduced residential solid fuel burning in low-income settlements in the study area.

A variety of open source tools for HIA are available to aid analysts. Using pre-designed tools to automate the HIA process offers several advantages including the simplification of the process and consistency and comparability among assessments. One major disadvantage is that analysts are often not aware of the assumptions built into each tool or their importance in the many different contexts in which they are used. Pre-designed tools are often designed for a specific assessment context, with very specific methodological approaches, geographical scopes, resolution and technical complexities aimed at assessing specific scenarios (Anenberg et al., 2016).

Two pre-designed tools were considered for use in this analysis, namely AirQ2.2 developed by the WHO, and BenMAP developed by the U.S. EPA. These tools were considered due to their ability to conduct analyses at the local, regional and global scale. Both of these models were designed to conduct urban analyses in developed regions (Europe and the United States), where residential solid fuel burning is not a source of great concern. These models also do not include the capability to run an analysis over one region using different control values for sub-areas within its borders. For these reasons, they were excluded for use in this analysis. To most accurately estimate the high spatial variability of PM$_{2.5}$ emissions from residential solid fuel burning, the 2011 census small area level dataset was used to deploy a land use type ordinary least squares regression model. Regressing the mean PM$_{2.5}$ concentration calculated for each monitoring site against variables known to be drivers of HAP can provide a clearer picture of where high population exposure due to residential solid fuel burning can be expected.

For this study, a predictive approach was chosen, as the aim was to assess the future impact of a specific intervention measure. To conduct the health and economic impact assessment, the well-

established health impact function approach recommended by the World Health Organization (WHO, 2006) and the U.S. EPA (Fann *et al.,* 2012) was followed. The process is represented by the following equation:

$$\Delta Y = Y_0 \, (1 - e^{\beta \Delta PM}) * Pop$$

In the context of this study, **ΔY** represents the change in the number of premature all-cause mortalities; **Y0** the baseline all-cause mortality incidence; **β** the risk coefficient (concentration-response function) derived from epidemiological studies; ΔPM the change in PM exposure after implementation of the intervention ($\mu g \, m^{-3}$) and **Pop** the size of the exposed population.

2.4.1   Choice of health outcome and Concentration Response function

This study aims to establish the long-term health and economic benefits of thermal insulation as an air pollution intervention measure in low-income settlements. Therefore, only long-term benefits associated with improved air quality was included in this analysis. To avoid double-counting $PM_{2.5}$ related premature deaths, the analysis was limited to include only long term all-cause premature mortality. Using all-cause mortality in health impact assessments is also recommended by the WHO (2001), as cause specific mortality data can often be unreliable. No reliable morbidity statistics were available for $PM_{2.5}$ related illness on such a small scale, thus only all-cause mortality was included in the assessment.

Concentration-response functions (CRF) are derived from epidemiological studies and represent the statistical relationship between a certain adverse health effect and ambient air pollution concentrations (Ostro, 2006). A literature review was conducted to identify CRFs from studies that assessed the relationship between long-term exposure to $PM_{2.5}$ and all-cause mortality. Most available studies were conducted in developed regions where the pollution mix and population characteristics differ from those of the study area. Ideally these should characteristics should match as closely as possible, but as no studies have been conducted in South Africa, it was necessary to extrapolate relative risk estimates from studies conducted in other countries.

The CRF from a cohort study conducted by Cao *et al.* (2011) in 31 Chinese studies between 1991 and 2000 was considered for use in this study due to the fact that the demographic profile and pollution mix could be more similar to that of South Africa. The CRF from the extended follow-up of the Harvard six cities study by Laden *et al.* (2006) was also considered. Ultimately, the CRF from the extended follow-up and spatial analysis of the American Cancer Society (ACS) cohort study by Krewski et al. (2009) was used. This choice was made due to the significant statistical power of this cohort study spanning 35 years and the fact that the study controlled for more covariates than the previously mentioned two. Their risk estimates for all-cause mortality were calculated using a

random effects Cox model that controlled for seven ecological and 44 individual covariates, based on average exposure levels for over 116 U.S. cities. They estimated an increase in relative risk of premature mortality in adults $\geq$ of 1.06% (95%CI 1.03-1.09) per 10μg/m^3 increase in PM.

This relative risk estimate was converted to the risk coefficient (β) needed to apply the health impact function by using the following calculation (U.S.EPA, 2015):

$$\beta = \frac{\ln(RR)}{\Delta pollution}$$

Where **ln** represents the natural log, **RR** the relative risk estimates of the study and Δ**pollution** the 10μg/m^3 used in the study.

2.4.2 Population data and mortality incidence

Population data from the 2011 census was used at the EA level to establish the number of people exposed in each area. The census dataset provides an age breakdown of the population in each EA and thus it was possible to calculate the population aged $\geq$30 years for each EA, to better match the CRF chosen for this study.

Table 2-4: Population and mortality incidence by municipality

Local Municipality	Total population > 30 years	Total Mortalities >30 years	Total population > 30 years	Mortality rate (deaths/100 000)	Mortality ratio used in HIA
Dipaleseng	18 024	181	18 024	1004	0.010042166
Ekurhuleni	1 430 625	19 950	1 430 625	1394	0.013944954
Emalahleni	172 128	2 641	172 128	1534	0.015343233
Govan Mbeki	122 991	1 757	122 991	1429	0.014285598
Lekwa	48 936	1 010	48 936	2064	0.020639202
Lesedi	45 012	2 218	45 012	4928	0.049275749
Msukaligwa	57 333	1 358	57 333	2369	0.023686184
Pixley Ka Seme	30 546	738	30 546	2416	0.024160283
Steve Tshwete	103 512	900	103 512	869	0.008694644
Victor Khanye	31 953	804	31 953	2516	0.025161957
City of Johannesburg	2 010 816	22 462	2 010 816	1117	0.011170589
Emfuleni	322 977	6 408	322 977	1984	0.019840422
Metsimaholo	65 736	1 037	65 736	1578	0.015775222
Midvaal	47 007	411	47 007	874	0.008743379

To calculate the baseline mortality incidence rate for each municipality in the study area, mortality by cause of death statistics for 2011 were obtained at the local municipality level from Statistics South Africa. This is the smallest scale at which mortality statistics by cause of death were available. Data were extracted according to the ICD 10 code for main cause of death (ICD 10 A00-Y98) for all deaths that occurred at age $\geq$30 in each municipality. The baseline mortality rate for each municipality was then calculated by dividing the total population $\geq$30 in each municipality by the total mortalities $\geq$30. This rate was applied to each EA within the administrative borders of each respective municipality. The population and mortality incidence data used for the HIA are summarised in Table 2-4.

2.4.3 Application of the health impact function

The required inputs for each EA (n=14 330) were compiled into a single dataset and the health impact function equation was applied to each EA using Δvalues of either $0\mu g/m^3$ or $4\mu g/m^3$. This approach ensured spatially refined estimates by using site specific air quality, population and mortality data for each EA. Results were then aggregated at the local municipality level for easier reporting.

When calculating the economic value of health benefits, we do not calculate the value of an individual life, but rather the sum of all small individual changes in risk (OECD, 2011). For this study, the Value of a Statistical Life (VSL) was used for economic valuation, as it is a widely used method to estimate the economic value of avoided premature mortality (Chanel, 2011; OECD, 2011; U.S. EPA, 2014, 2016).

2.4.4 Assumptions made in health impact estimation

The approach used for health impact estimations required making assumptions about future trends involving the study population, health outcomes, the time required to achieve decreased pollutant levels as well when health outcomes will occur (Pascal, 2011). Difficulties exist in projecting future changes in the demographic structure of a population due to factors such as migration, aging, changes in the health profile of a population and future mortality rates (Anenberg *et al.*, 2016). The assumptions made will likely result in an underestimation of health impacts. The main assumptions made in this study were:

- That the annual birth and mortality rates remain constant at the 2011 count, and that there will be no migration.
- That the intervention caused immediate reductions in PM$_{2.5}$ and that this has an immediate impact on health, continuing for 20 years

- That all PM$_{2.5}$ related averted deaths are attributable to exposure to the modelled air quality and pollutant of choice, occurring over a 20-year period, with the largest number of avoided deaths occurring in the earlier years.

2.4.5   Economic valuation of avoided premature mortaities

This study used the standard VSL recommended by the U.S EPA, as no standard VSL is available for South Africa. The standard U.S. EPA VSL was adapted for this study by using the benefits transfer technique. The benefits transfer technique involves adjusting the VSL from the original study context to reflect the differences in income, income growth, inflation and Purchasing Power Parity (PPP) over time and between study areas (Hammitt and Robinson, 2011; U.S. EPA, 2014). For this study, the U.S. EPA standard VSL (in US$ 2008) was converted to a 2011 South African Rand (ZAR) value using the following formula:

$$\text{VSL (ZAR 2011)} = \frac{VSL_{US,2008} \left(\frac{Y_{SA,2011}}{Y_{US,2008}}\right)^{elasticity} * PPP_{SA,2008} * CPI_{SA,2011}}{CPI_{SA,2008}}$$

Where:

- **VSL (ZAR 2011)** is the converted VSL value for South Africa in 2013 ZAR;
- **VSL$_{US, 2008}$** is the VSL value for the United States in 2008 US$;
- **Y** is the per capita GDP of South Africa and the United States in 2008, expressed in international (Purchasing Power Parity (PPP)-adjusted) dollars;
- **elasticity** represents the income elasticity of the VSL;
- **PPP$_{SA, 2008}$** is the PPP index in 2008 (in units of ZAR per International dollar) and;
- **CPI** represents the consumer price index for South Africa in 2011 and 2008 respectively.

All economic data for the US and South Africa were obtained from the World Bank Open Data database (World Bank Group, 2017).

In this case the elasticity adjustment value recommended by the U.S EPA (0.4) and the more conservative elasticity of (1.5) used by Leiman *et al.,* (2007) was used to calculate the VSL, for the purpose of comparison. The calculated VSL was then multiplied with the avoided premature mortalities estimated for each EA and aggregated at the local municipality level for reporting.

CHAPTER 3 - MANUSCRIPT 1

HEALTH IMPACT ASSESSMENT OF INTERVENTIONS TO REDUCE RESIDENTIAL SOLID FUEL BURNING: CHALLENGES AND CONSIDERATIONS

Abstract

Residential solid fuel burning is a major source of air pollution in South Africa. Household emissions not only greatly contribute to environmental degradation, but also to the burden of disease and public health costs both globally and locally. Reducing these emissions and their impacts could have substantial environmental, health and economic benefits. Currently, interventions aimed at reducing residential solid fuel burning are mainly implemented on the community scale and have had varying degrees of success; most resulting in only marginal improvements in air quality. The health impacts of these marginal improvements are however rarely considered and difficult to quantify. Health impact assessment (HIA) is a widely used tool for quantifying and predicting the heath impacts of improvements in air quality, but can HIA be effective and reliable at the community scale? Our study found the availability of reliable data at the appropriate scale to be the biggest challenge when conducting HIA in both the South African context and even more so at the community scale. Inputs needed to conduct HIA on any scale include air pollution concentration and exposure information, population data, background or baseline incidence of mortality and morbidity and appropriate concentration response (C-R) functions. Of all these parameters, only population data was found to be readily available and reliable at all scales. Other needed inputs can however be derived from international studies or by converting existing values, but this introduces uncertainties that have to be carefully considered when interpreting results. We conclude that HIA can be conducted at the community scale to aid decision making, but would be a more reliable tool once the necessary inputs are accessible and available for the South African context.

Keywords: air pollution interventions, economic valuation, economic benefits, health benefits, Health Impact Assessment, residential solid fuel burning

3.1   Introduction

In 2013, air pollution was responsible for 5.5 million premature deaths worldwide, ranking it as the leading environmental risk factor and the 4th overall risk factor (out of 79) for premature death and disease globally (Forouzanfar *et al.*, 2015; Brauer *et al.*, 2016). Total air pollution related deaths in South Africa for the same year were estimated to be 19 801. Of these deaths, 10 432 were attributable to ambient particulate matter pollution whilst the remaining 9 587 deaths were attributed to household air pollution (HAP) from solid fuel burning (IHME, 2015).

Considering that emissions from industrial, mining and other commercial sources are higher overall than those contributable to household combustion, these numbers support the evidence that exposure to HAP poses the most significant risk to human health (Ezzati & Kammen, 2002; WHO, 2015a). This is due to the fact that harmful pollutants are emitted at much lower levels where human exposure is at its highest. People are thus not only exposed to polluted indoor air, but also to polluted air in the near household environment, where individuals spend most of their time (Kirk R. Smith *et al*., 2014).

Population exposure to HAP and any consequent negative health effects is highly varied and inequitable both amongst and within countries and communities. The brunt of the burden of disease rests on the world's poor, where vulnerable populations like women, children, the elderly and sickly are by far the worst affected. Evidence shows the most common serious health consequence of HAP exposure to be acute respiratory diseases in children. Currently, more than half of deaths due to pneumonia in children under five can be attributed to HAP (Forouzanfar *et al.*, 2015; WHO, 2015a).

South Africa is no exception – many of our nation's poor live in densely populated low-income settlements where they are exposed to high concentrations of ambient and indoor air pollution. It is estimated that residential solid fuel burning contributed to 69% of all health impacts associated with fuel combustion in 2003, costing the South African economy R1.1 billion per year (FRIDGE, 2004). Reducing solid fuel burning in exposed communities thus has the potential to not only reduce air pollution, population exposure and associated negative health impacts, but will also result in considerable economic benefits.

In May 2015, the World Health Assembly adapted a landmark resolution aimed at addressing the health impacts of air pollution (WHO, 2015c). In this resolution, it is urged that Member States improve surveillance for all illnesses related to air pollution; promote clean cooking, heating and lighting technologies and fuels; strengthen expertise, technologies and scientific data in the field of air pollution; include health in all air pollution related policies; and monitor the effectiveness of air pollution control measures. The use of health impact assessments and cost-benefit analyses are

specifically mentioned and encouraged as a tool to measure control strategy effectiveness and inform decision making regarding air pollution policy (WHO, 2015b).

Despite the fact that South African air quality legislation and standards are driven by the impacts of air quality on human health, the Department of Environmental Affairs (DEA) is currently using an outcome based approach, with overall improvements in ambient air quality being the main focus of its policies and programmes. This includes the recently published Air Quality Offsets Guidelines that specifically mention residential solid fuel burning as a source to be included in offset programmes. Here it is once again stated that positive outcomes on air quality (i.e. reduced emissions) should be the main focus, with any other benefits being of secondary consideration (DEA, 2016). Considering that National Ambient Air Quality Standards (NAAQS) were developed specifically with the health of exposed populations in mind, should health benefits not be as important a measure of success as reductions in emissions?

Health impact Assessment (HIA) could be a useful tool to quantify the health and economic benefits of air pollution interventions. This paper aimed to identify and discuss the considerations and challenges involved in conducting HIA at the community scale.

3.2 Household energy use in South Africa

As a result of the Integrated National Electrification Programme (INEP), 85% of households in South Africa have access to electricity. Despite this remarkable improvement, many low-income households are still unable to afford electricity as their only energy source, and rely on multiple fuels to meet their energy needs (StatsSA, 2014). Burning solid fuels like wood, coal and dung are cost effective alternatives that provide energy for space heating and cooking simultaneously, with the added convenience of utilising the same appliance (Balmer, 2007; Naidoo *et al.*, 2014). Surveys show that low-income households exhibit this reliance on multiple energy sources regardless of their electrification status. This contradicts the prevailing energy transition theories that assume a straightforward shift from traditional to modern practices and appliances upon electrification and makes it a difficult source to manage (Barnes *et al.*, 2009). Furthermore, the type of solid fuel used by households vary greatly in both time and space. Rural/urban location, climatic conditions (especially space heating requirements during winter) and proximity to coalfields all influence the availability, choice and amount of fuel burned.

Rural households are typically more reliant on biomass fuels (mostly firewood) than those living in urban or peri-urban environments. The use of coal, although not very high at the national level, is prominent in many high density low-income urban and peri-urban settlements around our coalfields, where along with the heavy presence of industry, air pollution 'hot spots' form (Barnes *et al.*, 2009; DOE, 2013). South Africa thus faces a mix of air quality problems associated with both developed

and developing countries, with large populations exposed to pollution from industrial and household sources. This places a heavy burden on the public healthcare system (Diab *et al.*, 2006). This is reflected in the mortality results of the Global Burden of Disease Study of 2013 (IHME, 2015). In most of Sub-Saharan Africa and all our neighbouring countries, HAP is responsible for far more deaths than ambient particulate matter pollution. In South Africa however, HAP and ambient particulate matter pollution are responsible for roughly the same amount of deaths indicating that both industrial and household emissions are of great concern (Figure 3-1).
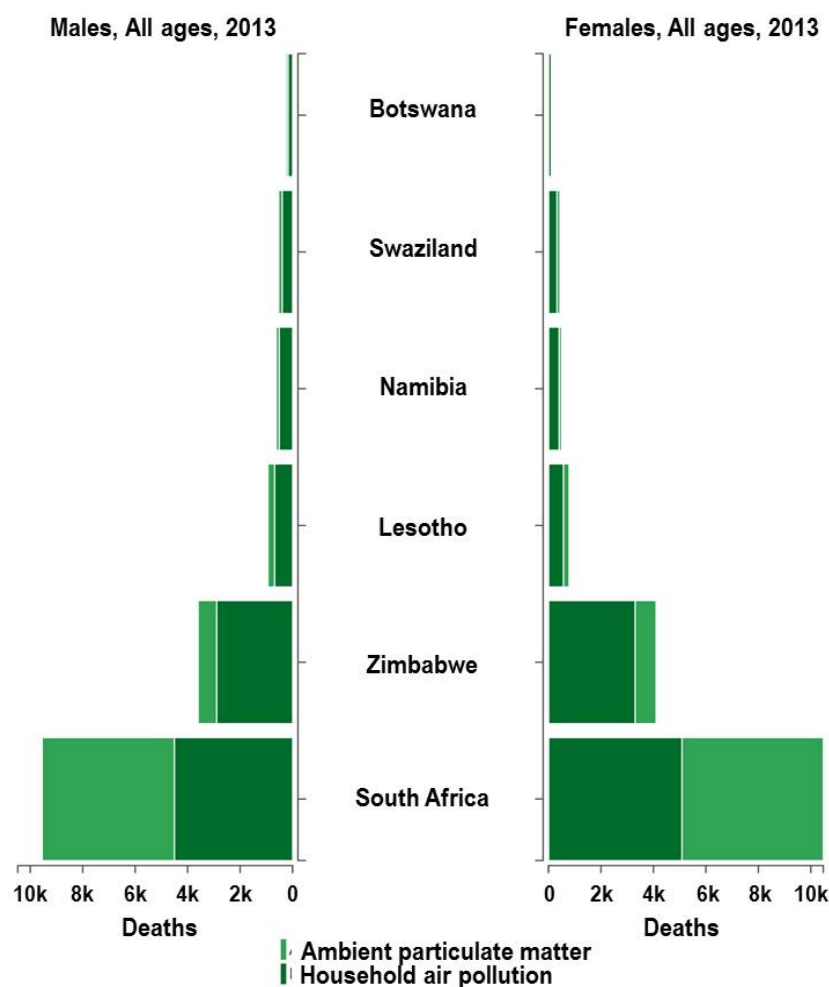
Figure 3-1: Air pollution related Mortality for South Africa and neighbouring countries in 2013 (Source: IHME, 2015).

This public health risk is increased further by other factors such as poverty, malnutrition and underdevelopment that increase vulnerability to the adverse effects of pollution exposure (Mathee & Wright, 2014). Peak emission times also coincide with periods of poor atmospheric dispersion potential, causing high pollution concentrations over residential areas, often referred to as townships

(Scorgie *et al.*, 2003; Wright & Diab, 2009). In many urban townships, solid fuel combustion has been shown to contribute to over 60% of particulate pollution levels at the local scale (Engelbrecht *et al.*, 2002). Air quality is expected to decline even more as urban areas become more populated. The current rate of urbanisation in South Africa is 1.59% and is expected to continue rising (CIA, 2016). Sustainable interventions are necessary to not only mitigate current pollution levels, but also to prevent air quality deteriorating further as the number of poor urban dwellers continue to grow.

3.2.1   Interventions to reduce residential solid fuel burning

Interventions aimed at reducing household burning in exposed communities have the potential to reduce air pollution exposure and associated negative health impacts. These interventions are also considered to have a "greater potential for positive, extensive and cost effective impacts compared to equivalent emissions from, for example, industrial emissions" (FRIDGE, 2004:28).

In the recently published air quality offsets guidelines, the DEA once again prescribes that an offset/intervention should be outcome based and focus primarily on overall improvements in ambient air quality within the airshed. Table 3-1 summarises the guiding principles as prescribed by the DEA. These principles, although sound, could prove problematic for companies implementing interventions targeting HAP to offset their emissions. Previous studies of interventions that involved the use of low-smoke stoves and fuels, alternative ignition methods and electrification revealed that these interventions did not significantly improve overall ambient air quality. Despite small or no detectable improvements in ambient air quality most of these interventions did however reduce the coal consumption and fuel costs of households. Health impact assessments revealed that health outcomes improved for all interventions, resulting in reductions in public health costs and loss of income from days missed at work (FRIDGE, 2004; Van Niekerk, 2006). Should these health and economic benefits to communities and our economy not be considered just as important a measure of success?

Ballard-Tremeer and Mathee (2000) argue that the main aim of interventions should be to bring about purposeful change in the household system in order to produce improvements in a wide variety of aspects (with the specific purpose of improved well-being). They recommend a framework to evaluate interventions from technical, economic and social perspectives - the degree of emission reduction should be only one of several perspectives to consider.

Von Schirnding *et al.* (2002) found that most available information pertaining to interventions and their performance relate to fuel consumption and direct emission levels. Our knowledge base is thus almost entirely restricted to source based interventions, with very little knowledge regarding long term performance or socio-economic benefits of any other types of interventions. They strongly

urge a shift of focus to a more holistic approach that considers other factors like long term sustainability and cost effectiveness, for example (Von Schirnding *et al.*, 2002).

Table 3-1: Offset guiding principles (Source: DEA, 2016).

DEA Principles	Description
Outcome based	Main outcome should be overall improvement in AQ in the airshed – other positive outcomes of secondary importance
Not "like for like"	Proposed interventions/offsets should address pollutants whose ambient concentrations are of concern in the area
Transparency & Acceptability	Should be based on open, fair and accountable administration. Public participation should be undertaken to ensure public buy-in
Additionality	Interventions/offsets should not be seen as substitutes for other efforts that can be made to reduce industrial emissions
Sustainability	Interventions/offsets must be based on long-term air quality improvement without impeding other socio-economic and environmental objectives
Measurable & scientifically robust	Interventions/offsets must have measurable outcomes and should be based on relevant and sound science

Health impact assessments could improve our understanding of the true impact, cost effectiveness and sustainability of different types of interventions and provide a more holistic approach to aid decision making.

3.3   Health Impact Assessment

The International Association for Impact Assessment (IAIA) defines health impact assessment as *"a combination of procedures, methods and tools that systematically judges the potential, and sometimes unintended, effects of a policy, plan, programme or project on the health of a population and the distribution of those effects within the population."* (Quigley *et al.*, 2006:1). HIAs are often used to estimate the impacts of various scenarios, including "business as usual" scenarios, and are useful to highlight the consequences of inaction and the need for mitigation measures. HIA should inform and influence decision making to better integrate health protection and promotion into plans and projects (Quigley *et al*., 2006) They can be conducted at various scales, from the global (Lim *et al.*, 2012) to regional (Pascal *et al.*, 2013); national (Norman *et al.*, 2007; Fann *et al.*, 2012) and local (Broome *et al.*, 2015).

In the air quality context, HIAs mostly use information from available epidemiological studies and routine environmental and health data to help estimate the impact of air quality improvements on a given population's health (Pascal *et al*., 2011).

3.3.1   Health impact assessment tools and inputs

There are a wide variety of HIA tools available; each with varying degrees of complexity and accessibility, but the majority follow the same methodology and need the same inputs (Ostro, 2006). Two relatively well known HIA software tools include the World Health Organisations' (WHO) AirQ+ tool and the United States Protection Agency's (U.S.EPA) BenMAP model, both open source and easily accessible. The HIA process is represented by the following equation:

$$\Delta Y = Y_0 \left(1 - e^{\beta \Delta PM}\right) * Pop \qquad \text{(Eq. 1)}$$

Where ΔY represents the change in the number of health effects of interest, Y_0 the baseline incidence of the health effect/s assessed, β the risk coefficient (concentration-response function) derived from epidemiological studies, ΔPM the change in pollutant exposure and Pop the size of the exposed population.

Inputs needed to conduct HIAs on any scale thus include: air pollution concentration and exposure information, population data, background or baseline incidence of mortality and morbidity and appropriate concentration response (C-R) functions (Ostro, 2006). Regardless of the tool chosen, it is important that the appropriate geographic scope, resolution and technical rigor are employed for each analysis (Anenberg *et al.*, 2016).

The following sections will discuss these data requirements in the South African context.

3.3.1.1 Air quality data

To assess the effect an intervention has on air quality and human health, baseline air quality conditions (where emissions have not yet been controlled) need to be established. This baseline scenario is then used as a reference against which the control scenario (post intervention) can be compared and analysed (Abt Associates Inc., 2012). Either modelled estimates and/or monitored data can be used in a HIA. This paper will only focus on the choice of pollutant typically used in HIAs and not the technical modelling or monitoring requirements.

Main pollutants emitted through residential burning include particulate matter (PM) <10 µm in diameter (PM_{10}), fine particulates <2.5 µm in diameter ($PM_{2.5}$), ultrafine particles <0.1 µm in diameter (UFP), carbon monoxide, formaldehyde, Sulphur oxides and polycyclic organic matter. PM_{10} (also known as thoracic or inhalable particles) contains within it the coarse ($PM_{10-2.5}$) and fine ($PM_{2.5}$) fractions, whilst $PM_{2.5}$ includes ultrafine particles. Particulate matter (PM) is implicated in the majority of epidemiological studies as the major contributor to both short- and long-term morbidity and mortality and is most frequently used in HIA as the marker of pollution (Ostro, 2006).

Epidemiological evidence for elevated mortality and morbidity risks is most strongly associated with $PM_{2.5}$ and ultrafine particles, whilst coarse particles and most gaseous pollutants have been found to not be as significant, being responsible for mostly irritant effects. Long term exposure to $PM_{2.5}$ is strongly linked with premature cardiovascular and respiratory mortality as well as increased risk of developing lung cancer and cardio pulmonary disease (Brook *et al.*, 2010; Kan *et al.*, 2007). Fine particulates are more harmful as they contain many toxic compounds absorbed onto their surfaces and penetrate much deeper into the lungs, where they can enter the bloodstream. It has been established that there is no safe level of $PM_{2.5}$; even short term exposure can increase mortality and morbidity (Peters & Pope, 2002; Pope & Dockery, 2006; Raghunandan *et al.*, 2008; Brook *et al.*, 2010; WHO, 2013).
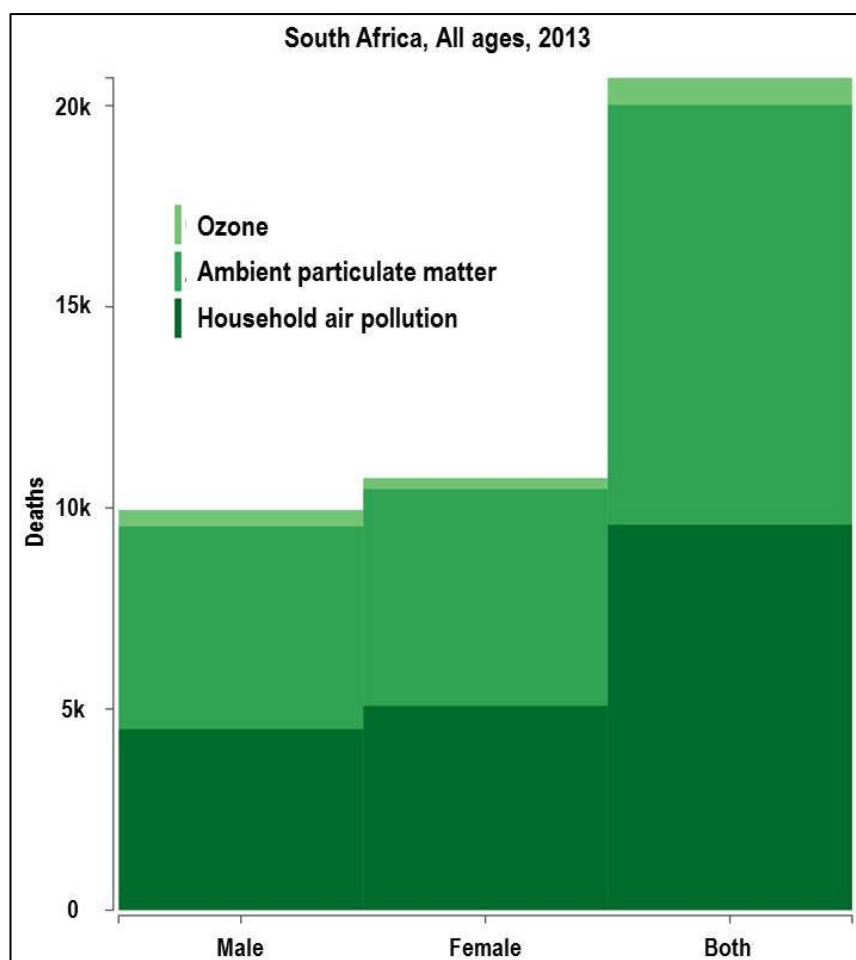
Figure 3-2: Deaths attributable to different pollutants for South Africa in 2013 (Source: IHME, 2015).

Ozone (O_3) is another pollutant of concern often included in HIAs; studies have reported associations between increased O_3 concentrations and short-term mortality and increased hospital admissions. The evidence on the effects of long term (chronic) exposure is much less conclusive though, and the strongest evidence of O_3 related health effects exists for summer months (Pascal

et al., 2013). Bruce *et al.* (2015) found the pollutants of most concern emitted during household combustion to be $PM_{2.5}$ and Carbon Monoxide (CO). O_3 is thus not an essential pollutant to include in analyses on HAP interventions. Worldwide, $PM_{2.5}$ is considered to serve as a general indicator of the anthropogenic pollution mix of concern and would be just as representative in South Africa. The burden of disease and mortality attributable to ambient particulate matter pollution in our country is far more significant than that of O_3 (Figure 3-2).

This does present a challenge; monitoring of $PM_{2.5}$ has only been done on a regular basis in the past decade or so and data is not always available. $PM_{2.5}:PM_{10}$ ratios can however be derived for specific locations and used in analyses (Ostro, 2006). For example, when estimating the burden of disease attributable to air pollution in South Africa, Norman *et al* (2007) converted PM_{10} concentrations to estimates of $PM_{2.5}$ by using available information on factors that may influence $PM_{2.5}:PM_{10}$ ratios. These included values derived from local studies where monitoring data were available for both fractions. Where no local data were available, the same approach used in the global air pollution risk assessment was followed.

3.3.1.2   Size and composition of exposed population

Human exposure is defined as "the event when a person comes into contact with a pollutant of a certain concentration during a certain period of time" (Ott *in* Janssen & Mehta, 2006:61). Thus, high pollutant concentrations do not necessarily result in health impacts - human exposure only occurs when people spend time in areas where pollutants are present. The 'dose' or amount of pollution that actually crosses one of the body boundaries will result in the health effect and varies amongst pollutants and individuals. As a result, the same source could have different health outcomes and impacts in different populations (Jansen & Mehta, 2006).

Reliable population data for the study area is thus of the utmost importance when conducting a HIA. Since many concentration response functions are specific to certain population sub groups (e.g. adults, children, women) demographic data that include these divisions will enable a more in depth HIA (Janssen & Mehta, 2006; Ostro, 2006). A full census is conducted by Statistics South Africa (StatsSA) every ten years, and large-scale community surveys annually. Population and household statistics are available at various scales, the smallest being at suburb or village level. Population statistics are easily accessible in various formats, usually free of charge or at minimum costs. Affordable, up to date and reliable population data is thus easy to access and should not impede the HIA process.

3.3.1.3 Background mortality and morbidity incidence

HIAs estimate the percentage of change in selected health effects per unit of pollution reduced/increased (change in relative risk). The baseline incidence rate of the health outcomes or endpoints included in the assessment is thus the third important input for HIA. The choice of health outcomes to include in an assessment is largely based on available evidence from epidemiological and scientific literature and the availability of data regarding baseline incidence rates. To be truly representative, incidence rates should ideally be collected at the place and scale of assessment (e.g. city, province, local municipality) and should match the age cohort being studied (Ostro, 2006).

Mortality and morbidity outcomes that are typically used in HIA include:

- Cardiovascular mortality.

- Respiratory Mortality.

- All-Cause Mortality.

- Mortality due to acute respiratory infections (ARI) (children <5).

- Asthma exacerbation.

- Respiratory and cardiovascular hospital visits.

- Acute and chronic bronchitis.

- Decreased lung function.

Ideally, an HIA should include both mortality and morbidity outcomes, but reliable morbidity and hospital admission information is very hard to gather in South Africa. Mekwa *et al.* (2016) found that the country's health research system is negatively impacted by the shortcomings in the data produced by routine national health information systems that typically have weak structures and performance profiles. Although structures and initiatives for the collection and collation of health data do exist in South Africa, none of these are comprehensive and provide limited coverage of different health conditions and geographic areas. They attribute these limitations to the lack of sufficient information policies, formal agreements and data management protocols between the various agencies that manage health data (Mekwa *et al.*, 2016). Applying baseline rates from original cohort studies to other areas can add large additional uncertainties, and conducting surveys to ascertain morbidity incidence and prevalence are costly and time consuming (Diab *et al*., 2006).

Mortality and causes of death statistics are available from StatsSA up to local municipality level and as result, cost effective HIA in South Africa would mostly estimate changes in premature mortality. Norman *et al.*, (2007), for example estimated the burden of disease attributable to PM exposure in

South Africa and used mortality due to cardiopulmonary disease and lung cancer amongst adults and ARI in children under 5 as health outcomes.

3.3.1.4 Concentration Response Functions

A concentration response (C-R) function represents the statistical relationship between pollutant concentrations and a selected health effect, based on evidence from epidemiological studies. The majority of air pollution related epidemiological studies have been conducted in developed countries, introducing some uncertainty when using them for populations in developing regions. No long-term epidemiological studies to establish local C-R functions have been conducted in South Africa and therefore, the most suitable C-R functions has to be identified from the current literature (Norman *et al.,* 2007). Care should be taken when choosing C-R functions for HIA, as various confounding factors including environmental conditions, the chemical composition of pollutants, individual susceptibility, geographical location and socio-economic status of the affected population can all influence human response to exposure. The uncertainties introduced by the above-mentioned variability should be included in any discussions about results.

3.3.1.5 Economic valuation of health benefits

Reduced premature mortality would be the most reliable health outcome to include in air pollution HIAs in South Africa, as discussed in previous sections. In order to calculate the economic value of estimated health benefits, a monetary value must be attached to avoided premature deaths in the population. An air pollution intervention lowers the risk of premature death by a small amount for a large population and this reduction in risk is what is known as a health benefit. Thus, calculating the monetary value of health benefits does not entail calculating the value of an individual life, but rather the sum of small individual changes in risk of premature death. The Value of a Statistical Life (VSL) is widely used for this type of economic valuation (Abt Associates Inc., 2012; OECD, 2011).

These values are based on studies that determine the amounts that people are willing to pay to reduce their risk of premature death due to a certain hazard. These values are then pooled together to derive the VSL. The VSL thus represents the amount a group is willing to pay to reduce mortality risk enough to save one life (Miller, 2000). Using the VSL for valuation is not without controversy (Ackerman & Heinzerling, 2002; Miller, 2000), but it still remains one of the most widely used methods to calculate the value of marginal changes in risk (Abt Associates Inc., 2012).

There is currently no agreed upon VSL for South Africa. Existing VSL values for other countries can, however, be adapted for South Africa by using the benefits transfer technique and making income adjustments (Miller, 2000; OECD, 2011). It is also recommended by the U.S EPA to adjust the

converted VSL for inflation, income growth, income elasticity and purchasing power parity (PPP). Making these adjustments reflect changes in real income over time (Hammitt & Robinson, 2011).

The VSL for South Africa in 2013 for example, was calculated to be ZAR 5 471 523 (2013 US$ 547 1523) after adjusting for purchasing power parity and inflation. The economic value of avoided deaths can be calculated by multiplying the health benefits (number of avoided deaths) of improved air quality by the VSL for the population. Every death avoided thus results in substantial economic benefits – even small-scale interventions at the community level could benefit not only the exposed communities, but also lessen the economic burden on households and the public healthcare system.

3.4 Conclusion

South Africa is faced with a complex mix of air quality management and development issues. Poor air quality affects our entire population, but those exposed to air pollution in their household settings bear the largest part of the health burden. This is thus not only an issue of environmental and economic concern, but also one of social justice.

Interventions aimed at reducing exposure to HAP in low-income settlements have the potential to reduce public health costs and improve the lives of millions of South Africans. Despite the fact that South African air quality legislation and standards are driven by the impacts of air quality on human health, the DEA is still using an outcome based approach, placing improvements in ambient air quality above socio-economic benefits.

This paper argued that a more holistic approach to addressing the problem is needed and investigated whether HIA could offer reliable insights in the South African context. Our study found the availability of reliable data at the appropriate scale to be the biggest challenge when conducting HIA in both the South African context and even more so at the community scale. Inputs needed to conduct HIA on any scale include air pollution concentration and exposure information, population data, background or baseline incidence of mortality and morbidity and appropriate concentration response (C-R) functions. Of all these parameters, only population data was found to be readily available and reliable at all scales. Other needed inputs can however be derived from international studies or by converting existing values, but this introduces uncertainties that have to be carefully considered when interpreting results. We conclude that HIA can be conducted at the community scale to aid decision making, but would be a more reliable tool once the necessary inputs are accessible and available for the South African context.

3.5   References

Abt Associates Inc. 2012. BenMAP environmental benefits mapping and analysis program: user's manual. Prepared for the Office of Air Quality Planning and Standards U.S. Environmental Protection Agency. North Carolina: Research Triangle Park.

Ackerman, F. & Heinzerling, L. 2002. Pricing the priceless: cost-benefit analysis of environmental protection. *University of Pennsylvania law review*, 150(5):1553.

Ballard-Tremeer, G. & Mathee, A. 2000. Review of interventions to reduce the exposure of women and young children to indoor air pollution in developing countries. Report prepared for the WHO/USAID consultation on indoor air pollution and health, Washington DC, 3-4 May 2000.

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., Thomas, E. & Bruce, N. 2009. Household energy, indoor air pollution and child respiratory health in South Africa. *Journal of energy in Southern Africa*, 20(1):4–13.

Brauer, M., Freedman, G., Frostad, J., Van Donkelaar, A., Martin, R.V, Dentener, F., Van Dingenen, R., Estep, K., Amini, H., Apte, J.S., Balakrishnan, K., Barregard, L., Broday, D.M., Feigin, V., Ghosh, S., Hopke, P.K., Knibbs, L.D., Kokubo, Y., Liu, Y., Ma, S., Morawska, L., Texcalac Sangrador, J.L., Shaddick, G., Anderson, H.R., Vos, T., Forouzanfar, M.H., Burnett, R.T. & Cohen, A. 2016. Ambient air pollution exposure estimation for the global burden of disease 2013. *Environmental science & technology*, 50(2016):79–88.

Brook, R.D., Rajagopalan, S., Pope, 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. *Circulation*, 121(21):2331–2378.

Broome, R.A., Fann, N., Navin, T.J., Fulcher, C., Duc, H. & Morgan, G.G. 2015. The health benefits of reducing air pollution in Sydney, Australia. *Environmental research*, 143(2015):19–25.

CIA (Central Intelligence Agency). 2016. The world factbook: South Africa. https://www.cia.gov/library/publications/the-world-factbook/geos/sf.html Date of access: 26 Jun. 2016.

DEA *see* South Africa. Department of Environmental Affairs.

Diab, R.D., Muller, E. & Matooane, M. 2006. Application of health risk assessment models to South African conditions. *South African geographical journal*, 88(2):159–165.

DOE *see* South Africa. Department of Energy.

Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G. & Egami, R.T. 2002. The comparison of source contributions from residential coal and low-smoke fuels, using CMB modeling, in South Africa. *Environmental science and policy*, 5(2):157–167.

Ezzati, M. & Kammen, D.M. 2002. The health impacts of exposure to indoor air pollution from solid fuels in developing countries: knowledge, gaps, and data needs. *Environmental health perspectives*, 110(11):1057–1068.

Fann, N., Lamson, A.D., Anenberg, S.C., Wesson, K., Risley, D. & Hubbell, B.J. 2012. Estimating the national public health burden associated with exposure to ambient PM 2.5 and ozone. *Risk analysis*, 32(1):81–95.

Forouzanfar, M. & GBD 2013 Risk Factors Collaborators. 2015. Global, regional and national comparative risk assessment of 79 behavioural, environmental/occupational and metabolic risks or clusters of risks in 188 countries 1990-2013: a systematic analysis for the global burden of disease study 2013. *Lancet*, 386(2015):2287–2323.

FRIDGE. 2004. Study to examine the potential socio-economic impact of measures to reduce air pollution from combustion. Final report submitted to the trade and industry chamber: fund for research into industrial development growth and equity (FRIDGE). Johannesburg: Bentley West Management Consultants.

Hammitt, J.K. & Robinson, L.A. 2011. The income elasticity of the value per statistical life: transferring estimates between high and low-income populations. *Journal of benefit-cost analysis*, 2(1):1-27.

IHME (Institute for Health Metrics and Evaluation). 2015. GBD compare. Seattle: University of Washington. http://vizhub.healthdata.org/gbd-compare Date of access: 23 Jun. 2016.

Janssen, N. & Mehta, S. 2006. Human exposure to air pollution. (*In* World Health Organization, *ed*. Air quality guidelines: global update 2005. Copenhagen.).

Kan, H., London, S.J., Chen, G., Zhang, Y., Song, G., Zhao, N., Jiang, L. & Chen, B. 2007. Differentiating the effects of fine and coarse particles on daily mortality in Shanghai, China. *Environment international*, 33(2007):376–384.

Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., Amann, M., Anderson, H.R., Andrews, K.G., Aryee, M., Atkinson, C., Bacchus, L.J., Bahalim, A.N., Balakrishnan, K., Balmes, J., Barker-Collo, S., Baxter, A., Bell, M.L., Blore, J.D., Blyth, F., Bonner, C., Borges, G., Bourne, R., Boussinesq, M., Brauer, M., Brooks, P., Bruce, N.G., Brunekreef, B., Bryan-Hancock, C., Bucello, C., Buchbinder, R., Bull, F., Burnett, R.T., Byers, T.E., Calabria, B., Carapetis, J., Carnahan, E., Chafe, Z., Charlson, F., Chen, H., Chen, J.S., Cheng, A.T.A., Child, J.C., Cohen, A., Colson, K.E., Cowie, B.C., Darby, S., Darling, S., Davis, A., Degenhardt, L., Dentener, F., Des Jarlais, D.C., Devries, K., Dherani, M., Ding, E.L., Dorsey, E.R., Driscoll, T., Edmond, K., Ali, S.E., Engell, R.E., Erwin, P.J., Fahimi, S., Falder, G., Farzadfar, F., Ferrari, A., Finucane, M.M., Flaxman, S., Fowkes, F.G.R., Freedman, G., Freeman, M.K., Gakidou, E., Ghosh, S., Giovannucci, E., Gmel, G., Graham, K., Grainger, R., Grant, B., Gunnell, D., Gutierrez, H.R., Hall, W., Hoek, H.W., Hogan, A., Hosgood, H.D., Hoy, D., Hu, H., Hubbell, B.J., Hutchings, S.J., Ibeanusi, S.E., Jacklyn, G.L., Jasrasaria, R., Jonas, J.B., Kan, H., Kanis, J.A., Kassebaum, N., Kawakami, N., Khang, Y.H., Khatibzadeh, S., Khoo, J.P., Kok, C., Laden, F., Lalloo, R., Lan, Q., Lathlean, T., Leasher, J.L., Leigh, J., Li, Y., Lin, J.K., Lipshultz, S.E., London, S., Lozano, R., Lu, Y., Mak, J., Malekzadeh, R., Mallinger, L., Marcenes, W., March, L., Marks, R., Martin, R., McGale, P., McGrath, J., Mehta, S., Mensah, G.A., Merriman, T.R., Micha, R., Michaud, C., Mishra, V., Hanafiah, K.M., Mokdad, A.A., Morawska, L., Mozaffarian, D., Murphy, T., Naghavi, M., Neal, B., Nelson, P.K., Nolla, J.M., Norman, R., Olives, C., Omer, S.B., Orchard, J., Osborne, R., Ostro, B., Page, A., Pandey, K.D., Parry, C.D.H., Passmore, E., Patra, J., Pearce, N., Pelizzari, P.M., Petzold, M., Phillips, M.R., Pope, D., Pope, C.A., Powles, J., Rao, M., Razavi, H., Rehfuess, E.A., Rehm, J.T., Ritz, B., Rivara, F.P., Roberts, T., Robinson, C., Rodriguez-Portales, J.A., Romieu, I., Room, R., Rosenfeld, L.C., Roy, A., Rushton, L., Salomon, J.A., Sampson, U., Sanchez-Riera, L., Sanman, E., Sapkota, A., Seedat, S., Shi, P., Shield, K., Shivakoti, R., Singh, G.M., Sleet, D.A., Smith, E., Smith, K.R., Stapelberg, N.J.C., Steenland, K., Stöckl, H., Stovner, L.J., Straif, K., Straney, L., Thurston, G.D., Tran, J.H., Van Dingenen, R., Van Donkelaar, A., Veerman, J.L., Vijayakumar, L., Weintraub, R., Weissman, M.M., White, R.A., Whiteford, H., Wiersma, S.T., Wilkinson, J.D., Williams, H.C., Williams, W., Wilson, N., Woolf, A.D., Yip, P., Zielinski, J.M., Lopez, A.D., Murray, C.J.L. & Ezzati, M. 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the global burden of disease study 2010. *The Lancet*, 380(9859):2224–2260.

Mathee, A. & Wright, C. 2014. Environmental health in South Africa. *South African health review*, 2013/2014:105–116.

Mekwa, N.J., Madela-Mntla, E.N., Loots, G., Van Niekerk, A., Jeenah, M. & Mayosi, B.M. 2016. The development of a national health research observatory in South Africa: considerations and

challenges. (*In* Padarath, A., King, J.E.M. & Casciola, J., *eds.* South African health review 2016. Durban: Health Systems Trust.).

Miller, T.R. 2000. Variations between countries in values of statistical life. *Journal of transport economics and policy*, 34(2):169–188.

Naidoo, S., Piketh, S.J. & Curtis, C. 2014. Quantification of emissions generated from domestic burning activities from townships in Johannesburg. *Data and methodology*, 24(1):34–41.

Norman, R., Cairncross, E., Witi, J. & Bradshaw, D. 2007. Estimating the burden of disease attributable to urban outdoor air pollution in South Africa in 2000. *South African medical journal,* 97(7):782–790.

OECD (Organization for Economic Cooperation and Development). 2011. Valuing mortality risk reductions in regulatory analysis of environmental, health and transport policies: policy implications. Paris.

Ostro, B. 2006. Health impact assessment. (*In* World Health Organization, *ed*. Air quality guidelines: global update 2005. Copenhagen.).

Pascal, M., Corso, M., Chanel, O., Declercq, C., Badaloni, C., Cesaroni, G., Henschel, S., Meister, K., Haluza, D., Martin-Olmedo, P. & Medina, S. 2013. Assessing the public health impacts of urban air pollution in 25 European cities: results of the Aphekom project. *Science of the total environment*, 449(2013):390–400.

Pascal, M., Corso, M., Ung, A., Declerq, C. & Medina, S. 2011. Improving knowledge and communication for decision making on air pollution and health in Europe (Aphekom): guidelines for assessing the health impacts of air pollution in European cities. Saint-Maurice: French institute for public health surveillance.

Peters, A. & Pope, C.A. 2002. Cardiopulmonary mortality and air pollution. *Lancet*, 360(9341):1184–1185.

Pope, C.A. & Dockery, D.W. 2006. Critical review: health effects of fine particulate air pollution: lines that connect. *Air & waste management association*, 709–742.

Quigley, R., Den Broeder, L., Furu, P., Bond, A., Cave, B. & Bos, R. 2006. Health impact assessment international best practice principles. Special publication series no. 5. Fargo: International association for impact assessment.

Raghunandan, A., Matooane, M. & Oosthuizen, R. 2008. Impacts of air pollution. Publication series b: book 5. Pretoria: Department of Environmental Affairs.

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. *The clean air journal*, 13(2):5–18.

Smith, K.R., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z., Dherani, M., Hosgood, H.D., Mehta, S., Pope, D. & Rehfuess, E. 2014. Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. *Annual review of public health*, 35(1):185–206.

South Africa. Department of Energy. 2013. A survey of energy related behaviour and perceptions in South Africa: the residential sector. Pretoria.

South Africa. Department of Environmental Affairs. 2016. National Environmental Management Act (107 of 1998): Air Quality Offsets Guideline. Pretoria.

StatsSA (Statistics South Africa). 2014. General Household Survey, 2013. Statistical release: P0318. https://www.statssa.gov.za/publications/P0318/P03182013.pdf Date of access: 20 Oct. 2017.

Van Niekerk, W. 2006. From technology transfer to participative design: a case study of pollution prevention in South African townships. *Journal of energy in Southern Africa*, 17(3):58–63.

Von Schirnding, Y., Bruce, N., Smith, K., Ballard-Tremeer, G., Ezzati, M. & Lvovsky, K. 2002. Addressing the impact of household energy and indoor air pollution on the health of the poor: implications for policy action. Paper prepared for the Commission on Macroeconomics and Health. Geneva: World Health Organization.

WHO (World Health Organization). 2013. Health Effects of Ambient Particulate Matter. Copenhagen.

WHO (World Health Organization). 2015a. Health and the environment: addressing the health impact of air pollution. Report by the secretariat for the sixty-eighth World Health Assembly. Agenda 68/18. Item 14.6. Geneva. http://apps.who.int/gb/ebwha/pdf_files/WHA68/A68_18-en.pdf. Date of access: 22 Jun. 2016.

WHO (World Health Organization). 2015b. World Health Assembly closes, passing resolutions on air pollution and epilepsy. http://www.who.int/mediacentre/news/releases/2015/wha-26-may-2015/en/ Date of access: 28 May 2015.

Wright, C.Y. & Diab, R. 2011. Air pollution and vulnerability: solving the puzzle of prioritization. *Journal of environmental health*, 73(6):56–64.

CHAPTER 4 - MANUSCRIPT 2

The health and economic benefits of thermal insulation interventions to improve air quality in a South African township

Abstract

The World Health Organization recently named exposure to air pollution from residential solid fuel burning the greatest global environmental human health risk today. These emissions pose such a great risk to human health because they are emitted in close proximity to where people live and spend most of their time. Populations that use solid fuels for their energy needs are also very often more vulnerable to the adverse health effects due to poverty and underdevelopment in their residential settings. Furthermore, the financial cost of air pollution related illness and deaths can place great strain on households and public healthcare systems. Interventions aimed at reducing residential burning have the potential to reduce air pollution related illness and deaths as well as their associated costs. This study estimated the health and economic benefits of such an intervention implemented in the low-income settlement of KwaDela, Mpumalanga. The intervention involved retrofitting houses with thermal insulation in order to determine whether improving the thermal comfort in dwellings would result in a reduction of solid fuel burning and $PM_{2.5}$ emissions. Sampling campaigns were conducted in cold and warm seasons, both pre- and post-intervention. The BenMAP-CE model was used to relate incremental improvements in air quality to the associated human health benefits (reduced mortality) and then calculated the monetary value of these improvements. The thermal insulation retrofit did not result in statistically significant $PM_{2.5}$ reductions, but did reduce coal consumption and improve the thermal comfort of residents. Health impact assessment results however indicated that estimated small reductions in $PM_{2.5}$ will improve both daily and long-term health outcomes in the community, resulting in significant economic benefits.

Keywords: Air pollution; Emission controls; Health effects/risks; Human exposure

4.1   Introduction

The World Health Organization (WHO) recently identified air pollution from residential solid fuel use as the greatest global environmental risk to human health (WHO, 2014). Worldwide the major burden of negative health impacts rests on the poor, and South Africa is no exception. Nationally,

85% of households have access to electricity, but many low-income households are unable to afford electricity as their only energy source and rely on multiple fuels for their energy needs (StatsSA, 2014). Biomass fuels and coal are cost-effective alternatives, as they provide energy for space heating and cooking simultaneously, with the added convenience of utilizing the same appliance (Balmer, 2007; Naidoo, Piketh & Curtis, 2014). It is estimated that close to 13 million South African households still rely on these fuels for some or all of their energy needs (Sustainable Energy Africa, 2014).

Although overall emissions from industrial, mining and other commercial sources are mostly higher than those contributable to household combustion, the impact of the latter on human health is of far bigger significance as these emissions result in higher population exposure (Ezzati & Kammen, 2002). Human exposure is defined as "the event when a person comes into contact with a pollutant of a certain concentration during a certain period of time" (Ott *in* Janssen & Metha, 2006:61). Thus, high pollutant concentrations do not necessarily result in health impacts - human exposure only occurs when people spend time in areas where pollutants are present. In these high density residential areas household members are not only exposed to polluted indoor air, but also to polluted air in the near household environment, where individuals spend most of their time (Smith *et al.*, 2014). In many parts of South Africa, peak emission times often coincide with periods of poor atmospheric dispersion potential, causing high pollution concentrations over low-income residential areas, also called townships (Scorgie *et al.*, 2003; Wright & Diab, 2009). Residential solid fuel burning has been estimated to contribute to over 60% of particulate pollution levels in some townships (Engelbrecht *et al.*, 2002).

Township residents are not only more likely to be exposed to higher levels of air pollution, but are also more vulnerable to the adverse health effects of this exposure due to poverty, the high prevalence of HIV/AIDS, malnutrition and historical underdevelopment in their residential settings (Mathee & Wright, 2014). A study commissioned by the Fund for Research into Industrial Development Growth and Equity (FRIDGE) in 2004 found that residential burning contributed to 69% of all health impacts associated with all fossil fuel combustion in 2003, costing the South African economy an estimated 1.1 billion South African Rand (ZAR) (2003 US$ 77 million) per year (FRIDGE, 2004). Household emissions thus not only contribute to environmental degradation and economic losses, but also have significant impacts on the nation's poor and disadvantaged communities. On the regional scale, the short-lived climate pollutants emitted by anthropogenic activities, including residential burning, have significant impacts on climate as they affect radiative forcing and cloud processes (Baker *et al.*,2015).

4.1.1 Health effects of residential PM$_{2.5}$ exposure

Main pollutants emitted through residential burning include particulate matter (PM) <10 μm in aerodynamic diameter (PM$_{10}$), fine particulates <2.5 μm in aerodynamic diameter (PM$_{2.5}$), ultrafine particles <0.1 μm in aerodynamic diameter (UFP), carbon monoxide, formaldehyde, Sulphur oxides and polycyclic organic matter. PM$_{10}$ (also known as thoracic or inhalable particles) contains within it the coarse (PM$_{10-2.5}$) and fine (PM$_{2.5}$) fractions, whilst PM$_{2.5}$ includes ultrafine particles. Because of this complex mixture of pollutants, epidemiological studies use only certain pollutants, including Ozone and PM, to serve as markers of the air pollution mixture (Pascal *et al*., 2011)

The health impacts of exposure to household air pollutants depend on factors that influence individual susceptibility such as age, developmental stage, gender, nutrition and socio-economic status. In the household environment, the most vulnerable populations include pregnant women, infants, young children and the elderly. Exposure to toxic air in the pre-natal and early post-natal life stages can permanently alter organ function, resulting in an increased likelihood of acute or chronic diseases surfacing at any life stage, from infancy to old age (Rollin, 2017). Strong evidence also exists to link exposure to household air pollution (HAP) to severe and fatal acute lower respiratory infections (ALRI) in children under five years of age (Bruce *et al*., 2015). Health impacts of adult HAP exposure include chronic obstructive pulmonary disease, lung cancer, cataracts, ischemic heart disease, stroke and cardiovascular mortality (Bruce *et al*., 2015; Pope *et al*., 2015).

Norman *et al.* (2007) estimated exposure to air pollution in South Africa to be responsible for 3.7% of the national mortality from cardiopulmonary diseases, 5.1% of mortality from cancers of the trachea, bronchus and lungs in adults over 30 years and for 1.1% of mortality from acute respiratory infections in children under 4 years old.

Epidemiological evidence for elevated mortality risks is most strongly associated with PM$_{2.5}$ and ultrafine particles, whilst coarse particles and most gaseous pollutants have been found to not be as significant, as they are mostly responsible for short term irritant effects. The strongest current evidence shows long term repeated exposures to PM$_{2.5}$ to have the largest impact on human health (Brook *et al*., 2010; Kan *et al*., 2007; WHO 2006). Fine particulates are more harmful as they contain many toxic compounds absorbed onto their surfaces and penetrate much deeper into the lungs, where they can enter the bloodstream. It has been established that there is no safe threshold for PM$_{2.5}$; even short term exposure (hours, days) can increase mortality and morbidity (Cao *et al*., 2010; Pope & Dockery, 2006).

Living in areas with high PM$_{2.5}$ levels has been linked with increased risk of respiratory, cardio- and cerebrovascular morbidity and mortality. Adverse health effects can range from acute to chronic and include anything from irritant effects to premature mortality. Evidence also exists that even small

reductions in $PM_{2.5}$ levels can decrease this risk in only a few years (Brook *et al.*, 2010; Peters & Pope, 2002; Pope & Dockery, 2006; Raghunandan *et al.*, 2008; WHO, 2013).

4.1.2   Interventions to reduce residential solid fuel burning

Interventions aimed at reducing household burning in exposed communities have the potential to reduce air pollution, population exposure and associated negative health impacts. They are generally divided into three broad categories: source based interventions (aimed at reducing emissions and the need for fire), environment based interventions (improved ventilation and housing design) and user based interventions (aimed at changing user behaviour). Successful implementation of an intervention requires an understanding of the local context and specific needs of the exposed community (Ballard-Tremeer & Mathee, 2000; Von Schirnding *et al.*, 2002). A participative approach must be followed to ensure that interventions are accepted and supported by the target community. Past interventions in townships, where the needs and values of communities were not considered, have been largely unsuccessful (Giles *et al.*, 2011; Mdluli, 2007; Van Niekerk, 2006). Cost of implementation (to implementing agencies and households) is another important factor to consider. High appliance, operating and/or maintenance costs often result in households reverting back to old technologies and habits. An integrated approach that considers not only reductions in emissions, but also all related costs, durability, ease of operation, maintenance needs, flexibility and convenience to users is most likely to result in the long-term acceptance and success of interventions (Ballard-Tremeer & Mathee, 2000; Von Schirnding *et al.*, 2002).

Previous studies of interventions implemented in the country (e.g. low-smoke stoves and fuels, alternative ignition methods and electrification) have had varied results in terms of air quality improvements (Scorgie *et al.*, 2001; FRIDGE, 2004; Van Niekerk, 2006, Leiman *et al.*, 2007). Because of this variability, it has been difficult to establish whether these attempts have had environmental and/or socio-economic impacts of enough significance to justify the costs of large scale implementation. These interventions did not significantly improve overall ambient air quality, but despite small or no detectable improvements in ambient air quality, the majority did reduce the coal consumption and fuel costs of households (Van Niekerk, 2006; Leiman *et al.*, 2007). Although it is now widely recognized that the long-term health benefits of an intervention should be considered an important indicator of its desirability and success, these health impacts are rarely quantified after implementation on the community scale (Von Schirnding *et al.*, 2002; WHO, 2014).

This study aimed to fill this gap by testing whether a decrease in ambient $PM_{2.5}$ that cannot be detected due to large variability, could still have significant health implications. This was done by estimating the health and associated economic benefits, in terms of reduced all-cause mortality, after the implementation of an air pollution intervention in the township of KwaDela, Mpumalanga. It also aimed to create a hypothetical scenario where air quality was "improved' enough to comply with

the future National Ambient Air Quality Standard for $PM_{2.5}$. This will provide a better understanding of the potential benefits of not only interventions, but also the enforcement of legislation on the community scale. Attaching a monetary value to these health benefits can also provide better insight into the viability of this type of intervention in terms of cost effectiveness and future benefits. Since the strongest evidence exists that both short- and long-term exposure to $PM_{2.5}$ contributes to premature mortality, it was the pollutant of focus of this study.

4.1.3   Study Area and intervention design

The township of KwaDela is situated on the South African Highveld, so called due to its location on a plateau that rises to elevations of 1800 m in the east and slopes to about 1200 m in the west. Southern Africa is dominated by anticyclonic circulation (and accompanying subsidence) throughout the year. Subsidence affects atmospheric dispersion and causes conditions highly favourable for the formation of both surface and elevated inversions. Surface inversions over the plateau are very frequent during winter months with depths of between 300-500 m resulting in poor pollutant dispersal (Tyson & Preston-Whyte, 2012). Due to rich coal reserves in the area, the Highveld accounts for 75% of the country's industrial activity and is well-known as an air pollution 'hotspot' (Collett *et al.*, 2010). Pollution levels are of such great concern here that the area has been declared a priority area for air quality management in terms of the National Environmental Management: Air Quality Act no.39 of 2004 (NEM: AQA) DEA, 2004). The township lies within the administrative borders of the Msukaligwa local municipality in the province of Mpumalanga, in the Highveld Priority Area (HPA). Msukaligwa has been identified as one of nine air quality "hotspots" within the HPA, where exceedances of National Ambient Air Quality Standards (NAAQS) are frequent (DEA, 2012). The community of KwaDela is very representative of low-income settlements on the Highveld in terms of household size, age and sex ratios, annual household income and employment status. KwaDela was chosen as the project site because of these population characteristics, along with its geographic location far from industrial and other urban sources, small population size (total population of 3786) and high levels of dependence on solid fuel burning for cooking and space heating. A quality of life survey conducted pre-implementation indicated that 790 out of the 1000 households in the township still used solid fuels to supplement their energy needs in 2013. This is not surprising considering that the average monthly household income in KwaDela was only ZAR 1 500 (US$ 150).

The project involved a pre-intervention sampling campaign in the cold and warm seasons of 2013-2014, followed by the retrofitting of 505 houses with thermal insulation from February to June 2014. Thermal insulation can be classified as a source based intervention, aimed at reducing the need for fire. This intervention meets the criteria mentioned earlier in that it is not only aimed at reductions in emissions, but also involves relatively low implementation costs and requires very little maintenance. It does not require changes in existing technology or behaviour and could be a sustainable long-

term intervention. Thermal insulation as intervention was effective elsewhere; residential coal consumption reduced by 50% in Poland after thermal modernization of 1970s single-family houses and ger inhabitants in Mongolia reported using 2.2kg less coal per day after adding additional felt insulation layers to their homes (Kerimray *et al*., 2017).

Figures. 4-1 and 4-2 indicate the locations of the study site and ambient sampling station and an expanded view of KwaDela and the surrounding area respectively.
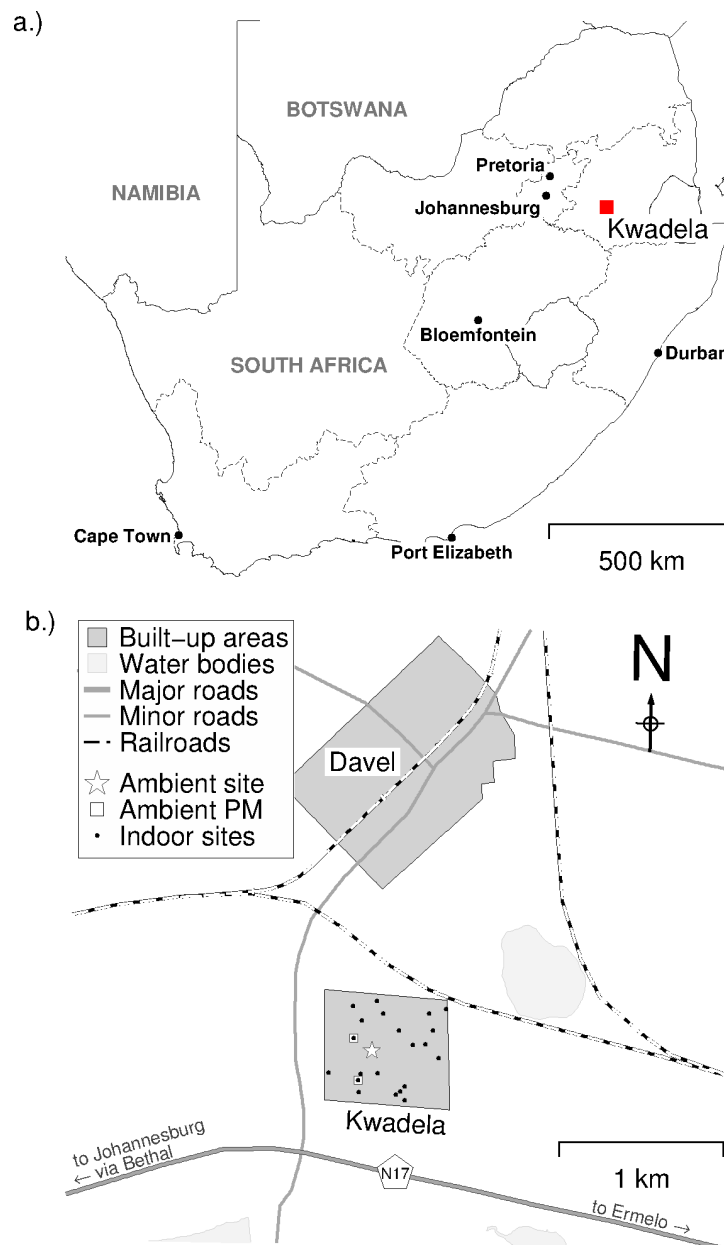
Figure 4-1: (a) Location of KwaDela in Mpumalanga and (b) Expanded view of the area surrounding KwaDela and location of sampling sites.
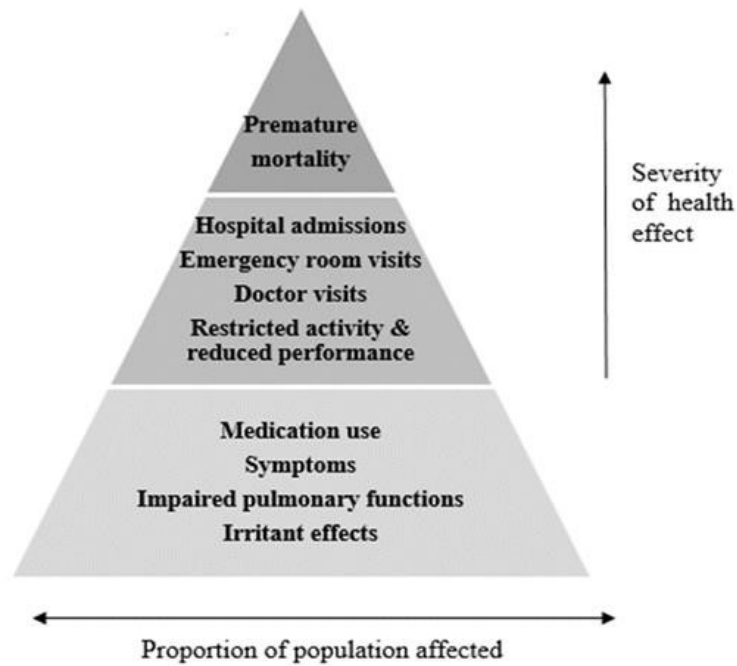
Figure 4-2: The inverse relationship between the frequencies of occurrence of health effects and their severity. Irritant and acute affects are for more common that chronic, severe effects and mortality (adapted from WHO, 2001).

4.2   Data and Methods

The United States Environmental Protection Agency's (U.S. EPA) Environmental Benefits mapping and Analysis Program – Community Edition version 1.1 (BenMAP-CE) was used to estimate the health and related economic benefits of the intervention. BenMAP-CE has been used to estimate the health benefits of air quality improvements in different countries and contexts around the world, but never at a scale so small as that of KwaDela (Boldo *et al.*, 2014; Broome *et al.*, 2015; Ding *et al.*, 2016; Fann *et al.*, 2012). BenMAP-CE estimates impacts on health by employing a health impact function (HIF) that is calculated by inputs from epidemiological literature and site-specific air quality and population data. This relationship is then applied to the exposed population and the economic value of any avoided health effects are calculated by using user defined valuation functions (Abt Associates Inc., 2012). The BenMAP-CE process is represented by the following equation:

$$\Delta Y = Y_0 \left(1 - e^{\beta \Delta PM}\right) * Pop$$

Where ΔY represents the change in the number of health effects of interest (premature all-cause mortality), Y_0 the baseline incidence of the health effect (Total all-cause mortalities/Total population in study area), β the risk coefficient (concentration-response function) derived from epidemiological studies, ΔPM the change in PM exposure ($\mu g \ m^{-3}$) and Pop the size of the exposed population. The following sections will discuss the data and methods used to derive the required inputs.

4.2.1   Baseline mortality incidence

The baseline mortality incidence rate is an estimate of the average number of people that die in a population over a certain period, due to all causes including air pollution (Abt Associates Inc., 2012). To avoid double-counting $PM_{2.5}$ related premature deaths, the analysis was limited to quantifying the effect of air quality improvements on daily and long term all-cause premature mortality. Using all-cause mortality in health impact assessments is also recommended by the WHO (2001), as cause specific mortality data can often be unreliable. Using all-cause mortality also ensures that air pollution related causes of death not yet known are included in analyses. No reliable morbidity statistics were available for $PM_{2.5}$ related illness on such a small scale, thus only all-cause mortality was included in the assessment.

Mortality and cause of death statistics for the Msukaligwa local municipality (2013) were obtained from Statistics South Africa (StatsSA). This is the smallest scale at which reliable mortality statistics were available. Hubbell, Fann and Levy (2010) recommend that baseline incidence rates should ideally be as spatially refined as possible, but recognise that many constraints exist and data might not always be available at the local scale. They recommend using various estimation and interpolation techniques to infer baseline rates where appropriate.   Using these techniques do however introduce significant uncertainties and is mostly used to estimate morbidity incidence rates. Casper (2008) used BenMAP to conduct a global scale health impact analysis and used mortality incidence rates at the country specific level, as this was the finest resolution available. The smallest level of mortality data available for South Africa is the municipality level. The population of the chosen municipality is a fair representation of the community of KwaDela and using data at this level would introduce less uncertainties than other estimation techniques.

Baseline incidence for KwaDela was estimated by multiplying the KwaDela: Msukaligwa population ratio with the incidences of non-accidental deaths in Msukaligwa. The baseline all-cause mortality incidence of 42 per 1000 was then converted to a mortality rate (total population/total mortality) and used as an input for BenMAP-CE.

4.2.2   Air Quality Data

Baseline air quality conditions, where emissions have not yet been controlled need to be established to effectively assess the impact of an intervention. This baseline scenario is used as a reference against which the control scenario (post intervention) can be compared and analysed (Abt Associates Inc., 2012).

$PM_{2.5}$ was measured using a Met-One E-bam sampler deployed in the community during two pre-intervention and two post-intervention sampling campaigns. Figure 5-1(b) indicates the central

location of the ambient sampling station in the community (29.664, -26.463). The monitoring site was visited every 2 weeks. Quality assurance was conducted by flagging all time periods as missing where instrument malfunctions were logged during the visits. Automatic checks, including buddy checks, typical concentrations for similar areas, and stuck values, were performed. Suspicious values were flagged and data was inspected manually to determine the validity of the potential problems. The data for any problem periods were set to missing. The most common problem was the mechanical failure of the filter tape advancement. The data for any problem periods were set to missing. Data retention for both sampling campaigns are shown in Table 4-1.

Table 4-1: Pre- and post-intervention PM$_{2.5}$ sampling results (µg m^{-3}).

Sampling Period	Count	Mean	S.D.	Min.	50%	99%	Max	Data Retention
Winter 2013	63	35	12	12	35	82	89	78%
Winter 2014	69	30	9	12	29	50	50	52%
Summer 2014	47	20	14	1	19	60	68	91%
Summer 2015	62	18	4	11	18	32	35	96%

Pre- and post-intervention seasonal monitored mean values (for both the cold and warm months) were then entered into BenMAP-CE, to calculate the Δ value of PM reductions. It was decided to "improve" air quality by this increment until concentrations complied with the target NAAQS of 24 µg m^{-3} (also the current WHO guideline). These values were used to create hypothetical control scenarios in BenMAP in order to calculate the health benefits of each level of improvement.

4.2.3   Concentration Response (C-R) functions

C-R Functions derived from epidemiological studies are used to relate a unit change in air pollutant to a change in the health outcome of interest. Various confounding and interactive factors including environmental conditions, the chemical composition of pollutants, individual susceptibility, geographical location and socio-economic status of the affected population can influence human response to exposure (Finkelstein *et al.*, 2005; Giles *et al.*, 2011; Ou *et al.*, 2008; Von Schirnding *et al.*, 2002). The majority of air pollution related epidemiological studies have been conducted in developed countries, introducing some uncertainty when using them for populations in developing regions. No long term epidemiological studies to establish local C-R functions have been conducted in South Africa and therefore, suitable C-R functions had to be identified from the current literature.

 The C-R function from a Chinese study (ages 0-99) by Kan *et al.* (2007) was selected for our analysis of the daily effects of PM$_{2.5}$ exposure on all-cause mortality. This C-R Function was selected

because as a developing nation, the socio-economic conditions and pollutant mix in China are more representative of those in South Africa compared to those in more developed countries. For long-term effects, the C-R function from the extended follow up of the Harvard Six Cities Study (ages 25-99) by Laden *et al.* (2006) was used. This C-R function was chosen because of the statistical power of a cohort study spanning more than 20 years. The extended follow up study observed significant associations between $PM_{2.5}$ and mortality and was able to evaluate the effect of changing average $PM_{2.5}$ concentrations since the original enrolment (mid 1970s) and first follow-up period (until 1990) of the study. When quantifying long term health impacts, the U.S. EPA assumes that reductions in premature deaths are distributed over a 20-year period, with the largest number of deaths avoided occurring in the earlier years (Fann *et al.*, 2012). This study makes the same assumption. For the purposes of this study, the intervention is also assumed to be maintained for 20 years.

Ideally, a health impact assessment should include a broad spectrum of related health effects, both acute and chronic. The frequency of the occurrence of air pollution related health impacts is very often inversely related to their severity, as illustrated in Figure 5-2. The total air pollution related health outcomes in an area are mostly dominated by less severe but more frequent impacts (WHO, 2001). Since no reliable morbidity data for the community was available, this assessment only included premature mortality and thus, represents the proverbial "tip of the iceberg".

4.2.4 Economic benefits of estimated avoided premature deaths

In order to calculate the economic value of health benefits, a monetary value must be attached to avoided premature deaths in the population. An air pollution intervention lowers the risk of premature death by a small amount for a large population and this reduction in risk is what is known as a health benefit. Thus, calculating the monetary value of health benefits does not entail calculating the value of an individual life, but rather the sum of small individual changes in risk of premature death (Abt Associates Inc., 2012; OECD, 2011). This study used the Value of a Statistical Life (VSL) for economic valuation.

Stated preference methods are preferred to evaluate the economic value of environmental policies and interventions aimed at improving health. These values are based on studies that determine the amounts that people are willing to pay to reduce their risk of premature death due to a certain hazard. These values are then pooled together to derive the VSL. The VSL thus represents the amount a group is willing to pay to reduce mortality risk enough to save one life (Miller, 2000). Using the VSL for valuation is not without controversy (Ackerman & Heinzerling, 2002; Miller, 2000), but it still remains one of the most widely used methods to calculate the value of marginal changes in risk (Abt Associates Inc., 2012).

There is currently no agreed upon VSL for South Africa. Existing VSL values for other countries can, however, be adapted for South Africa by using the benefits transfer technique and making income adjustments (Miller, 2000; OECD, 2011). It is also recommended by the U.S EPA to adjust the converted VSL for inflation, income growth, income elasticity and Purchasing Power Parity (PPP). Making these adjustments reflect changes in real income over time (Hammitt & Robinson, 2011). For this study, the U.S EPA's standard VSL (in US\$ 2008) was converted to 2013 South African Rand (ZAR) using the following formula:

$$VSL_{SA,2013} = \frac{VSL_{US,2008} \left(\frac{Y_{SA,2008}}{Y_{US,2008}}\right)^{elasticity} * PPP_{SA,2008} * CPI_{SA,2013}}{CPI_{SA,2008}} \quad (2)$$

Where $VSL_{SA, 2013}$ is the converted VSL value for South Africa in 2013 ZAR; $VSL_{US, 2008}$ is the VSL value for the United States in 2008 US\$; Y is the per capita GDP of South Africa and the United States in 2008, expressed in international (Purchasing Power Parity (PPP)-adjusted) dollars and *elasticity* represents the income elasticity of the VSL. In this case the U.S. EPA recommended value of 0.40 was used. $PPP_{SA, 2008}$ is the PPP index in 2008 (in units of ZAR per International dollar) and *CPI* represents the consumer price index for South Africa in 2013 and 2008 respectively. All economic data for the US and South Africa were obtained from the World Bank Open Data database (World Bank Group, 2017).

The VSL for South Africa in 2013 was calculated to be ZAR 5 471 523 (2013 US\$ 547 1523) after adjusting for purchasing power parity and inflation. BenMAP calculates the economic value of avoided deaths by multiplying the health effects of improved air quality by the VSL for the population.

4.3 Results and discussion

During colder months, concentrations remained elevated throughout the night, as a result of a low mixing boundary layer caused by the formation of surface inversions on all cloud free nights. Exceedances of NAAQS for $PM_{2.5}$ (65 µg m^{-3}) were measured 17 times during the cold season monitoring period (n~63) and four times during the warmer months (n~47). When compared to the 2016 $PM_{2.5}$ NAAQS of 40 µg m^{-3}, $PM_{2.5}$ levels very frequently exceeded this level in the ambient environment, especially during the colder months.

Post intervention sampling revealed a small observable $PM_{2.5}$ reduction during peak heating hours in the cold months, but almost no reduction in warmer months. Significant reductions were observed between maximum daily averages (mostly on coldest says). A comparison of pre- and post-intervention measurements for both the warm and cold season sampling campaigns is summarized in Table 4-1.

The question this study aimed to answer was whether the impact on health could be significant even though the difference in ambient concentrations was real, but not detectable.

The standard deviation of PM2.5 in KwaDela was on the same order of magnitude as the mean. This large variability would make it difficult to detect relatively small decreases due to planned interventions. The effect size is a common measure of the difference between two means. For the purpose of the paper, Cohen's definition of the effect size as the difference between the two means as a fraction with standard deviation of the sampled is used (Cohen, 1988). He defined an effect as small (d=0.2), medium (d=0.5) and large (d=0.8) and suggested that small and medium effects will be difficult to detect in the natural environment. In this case, effect size (d-value) represents the difference between the two means (pre-and post-intervention) and was used to estimate the effect the intervention had on the ambient air quality in KwaDela. For this campaign, the difference did not obtain statistical significance (d=0.6). Baseline and control values and their effect sizes are summarized in Table 4-2.

Table 4-2: Control values used to estimate health benefits and their d values.

Ambient Concentration ($\mu g/m^{-3}$)	PM$_{2.5}$ Reduction ($\mu g/m^{-3}$)	Cohen's d	Effect Size
32	4	0.3	Small
28	8	0.6	Medium
24	12	1	Large

The d values for both the cold and warm months indicate that the intervention had a small effect on PM$_{2.5}$ concentrations and the largest reduction in mean concentrations was observed in the cold months. Exceedances of the 24 hour NAAQS reduced to nine (days sampled:n~69) in the cold season and zero in the warmer months (days sampled:n~62). Thus, even though there was improvement, air quality in KwaDela did not improve enough to comply with the NAAQS, as exceedances are allowed only four times per annum. It is also important to note that concentration levels of pollutants and subsequent population exposure may vary significantly over space and time, this study uses estimated reductions but cannot state with absolute certainty that the intervention alone was the cause of these improvements in air quality. It does not take reductions in personal exposure or reductions in other possible sources of ambient emissions into account.

4.3.1   Health and economic benefits

Health impact assessment results revealed that the estimated reduction in PM$_{2.5}$ did not have a significant impact on daily all-cause mortality (Table 4-3). Results do however reflect small

reductions in risk and would have yielded higher results in a larger population. A monetary value can still be calculated for these results, as the VSL represents the sum of the small reductions in the risk of pre-mature mortality rather than the value of one individual life saved. Reductions in daily mortality risks are most likely to benefit those in the population that are already frail and vulnerable due to other chronic or transient conditions (WHO, 2001). Exposure to indoor emissions will also be reduced if less coal is burned, this study did however not take reductions in personal exposure into account. Health impact assessment results show that the estimated small post-intervention air quality improvement, if sustained over the assumed 20-year period, could reduce long term premature all-cause mortality in KwaDela (Table 4-3). BenMAP-CE calculated that the estimated 4 µg/m^{-3} reduction would, in the long term, result in two avoided premature deaths. The economic benefit of these avoided deaths was calculated to be in excess of ZAR 9.8 million (2013 US$ 980 000) (Table 4-3). The hypothetical reduction of 12 µg/m^{-3} would result in compliance with the WHO recommended 24 h PM$_{2.5}$ guideline of 25 µg/m^{-3} and this improvement will avoid five premature deaths. This value is also the target guideline set by the DEA, and will become the South African NAAQS for PM$_{2.5}$ in 2030. The economic benefit of an improvement of this magnitude in the small community of KwaDela alone was estimated to be just over ZAR 28.1 million (2013 US$ 2.8 million). When comparing the economic benefits of avoided deaths with the direct material and labour costs of the intervention – ZAR 6.5 million (2013 US$ 650 000) (Figure 4-3) – it is evident that it could have significant long term economic benefits, even at the small estimated reductions in PM$_{2.5}$ concentrations. A cost benefit analysis conducted by Leiman *et al.* (2007) estimated the economic benefit of thermal insulation interventions in only 5% of solid fuel burning households on the Highveld to be ZAR 226 million in 2003 (2003 US$ 30 million). Insulation in 20% of households was estimated to be ZAR 904 million in the same year (2003 US$ 120 million). These conclusions support our findings.

Table 4-3: Avoided all-cause premature mortality and associated economic benefits.

PM2.5 Reduction (µg m^{-3})	Ambient Concentration (µg/m^{-3})	Reduced daily all-cause mortality	Monetary Benefit (2013 US$)	Reduced long term all-cause mortality	Monetary Benefit (2013 US$)
4	32	0.06	32 8291	2	9 848 741
8	28	0.12	65 6582	3	18 329 602
12	24	0.18	98 4874	5	28 123 628
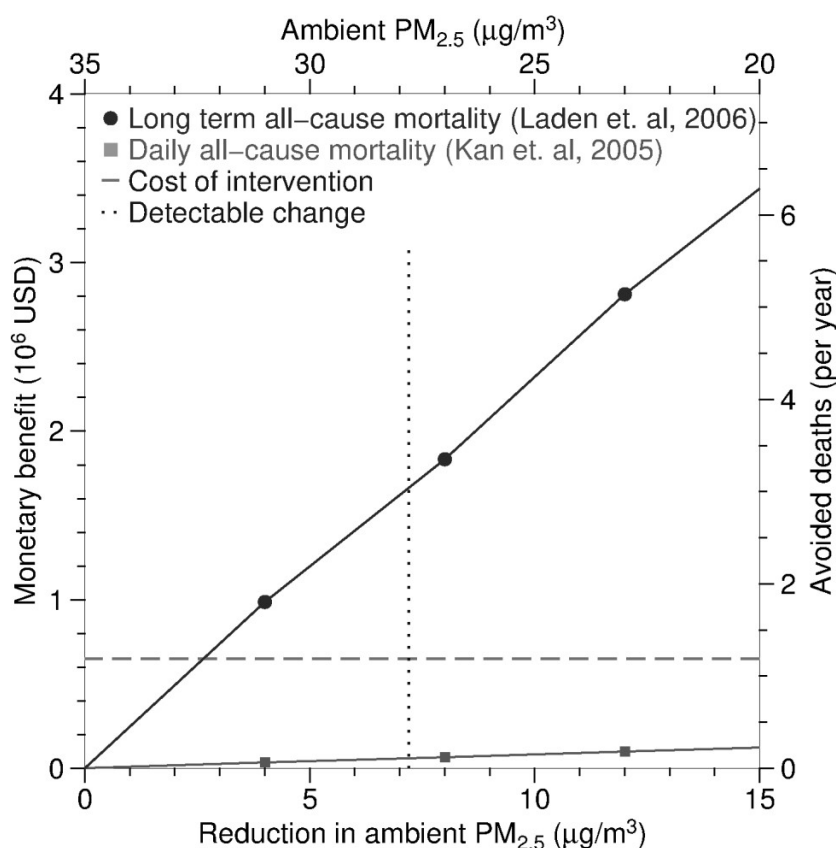
Figure 4-3: Long- and short-term health and economic benefits of incremental air quality improvements in KwaDela.

Economic benefits were calculated only for $PM_{2.5}$ related mortality in one small community, based on an estimated reduction in mean concentrations.

Reductions in other pollutants, cost of illness, loss of income due to days missed at work, and household savings in fuel costs were not considered, thus the true economic benefit of the intervention could be much higher. These results reiterate the need to not only consider reductions in emissions when implementing interventions and determining their success in the residential sector. Even small reductions will have significant health benefits for vulnerable populations exposed to high residential emissions on a daily basis. These results represent only 1000 of the 13 million exposed households in South Africa. Small reductions on a large scale have the potential to reduce the public health burden significantly and improve the lives of millions of South Africans.

4.4 Conclusion

A large number of South Africa's citizens are exposed to household air pollution on a regular basis. Interventions aimed at reducing emissions from residential solid fuel use could reduce this exposure and associated health impacts. This study estimated the health and economic benefits of thermal insulation as an intervention measure on the community scale. Results revealed that even small

reductions in ambient $PM_{2.5}$ concentrations could have health benefits for the population of KwaDela. Adding an economic value to these health benefits helped to highlight the true impact of the intervention and revealed that the economic benefits could outweigh direct implementation costs in the long term. Health impact assessments, even at such a small scale could provide better insight when evaluating the effectiveness of community based interventions. This said, economic benefits should only be one of various factors to consider and must not be considered more significant than improving and extending the lives of South Africa's poor and vulnerable communities. This study revealed that small reductions have significant health and economic benefits even at a very small scale. These benefits continue long after implementation and should be considered just as important as post intervention air quality measurements. If emissions could be reduced at the national scale, even by margins considered statistically insignificant, it can be expected that the South African population and economy would benefit immensely.

4.5   REFERENCES

Abt Associates Inc. 2012. BenMAP environmental benefits mapping and analysis program: user's manual. Prepared for the Office of Air Quality Planning and Standards U.S. Environmental Protection Agency. North Carolina: Research Triangle Park.

Ackerman, F. & Heinzerling, L. 2002. Pricing the priceless: cost-benefit analysis of environmental protection. *University of Pennsylvania law review*, 150(5):1553.

Ballard-Tremeer, G. & Mathee, A. 2000. Review of interventions to reduce the exposure of women and young children to indoor air pollution in developing countries. Report prepared for the WHO/USAID consultation on indoor air pollution and health, Washington DC, 3-4 May 2000.

Balmer, M. 2007. Household Coal Use in an Urban Township in South Africa. *Journal of energy in Southern Africa*, 18(3):27–32.

Boldo, E., Linares C., Aragones, N., Lumbreras, J., Borge, R., De la Paz, D., Perez-Gomez, B., Fernandez-Navarro, P., Garcia-Perez, J., Pollan, M., Pamis, R., Moreno, T., Karanasiou, A. & Lopez-Abente, G. 2014. Air quality modelling and mortality impact of fine particles reduction policies in Spain. *Environmental research*, 128(2014):15–26.

Brook, R.D., Rajagopalan, S., Pope, 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. *Circulation*, 121(21):2331–2378.

Broome, R.A., Fann, N., Navin, T.J., Fulcher, C., Duc, H. & Morgan, G.G. 2015. The health benefits of reducing air pollution in Sydney, Australia. *Environmental research*, 143(2015):19–25.

Bruce, N., Pope, D., Rehfuess, E., Balakrishnan, K., Adair-Rohani, H. & Dora, C. 2015. WHO indoor air quality guidelines on household fuel combustion: strategy implications of new evidence on interventions and exposure–risk functions. *Atmospheric environment*, 106(2015):451–457.

Cao, J., Yang, C., Li, J., Chen, R., Chen, B., Gu, D. & Kan, H. 2011. Association between long-term exposure to outdoor air pollution and mortality in China: a cohort study. *Journal of hazardous materials,* 186(2011):1594–1600.

Casper, S. 2008. Using EPA's environmental benefits mapping and analysis program (BenMAP) for global health impact analysis. Chapel Hill: University of North Carolina.

Cohen, J. 1988. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale: Lawrence Earlbaum Associates.

Collett, K.S., Piketh, S.J. & Ross, K.E. 2010. An assessment of the atmospheric nitrogen budget on the South African Highveld. *South African journal of science*, 106(5/6):1–9.

DEA *see* South Africa. Department of Environmental Affairs.

Ding, D., Zhu, Y., Jang, C., Lin, C., Wang, S., Fu, J., Gao, J., Deng, S., Xie, J. & Qiu, X. 2016. Evaluation of health benefit using BenMAP-CE with an integrated scheme of model and monitor data during Guangzhou Asian Games. *Journal of environmental sciences (China)*, 42(2016):9–18.

Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G. & Egami, R.T. 2002. The comparison of source contributions from residential coal and low-smoke fuels, using CMB modelling, in South Africa. *Environmental science and policy*, 5(2):157–167.

Ezzati, M. & Kammen, D.M. 2002. The health impacts of exposure to indoor air pollution from solid fuels in developing countries: knowledge, gaps, and data needs. *Environmental health perspective*s, 110(11):1057–1068.

Fann, N., Lamson, A.D., Anenberg, S.C., Wesson, K., Risley, D. & Hubbell, B.J. 2012. Estimating the national public health burden associated with exposure to ambient PM 2.5 and ozone. *Risk analysis*, 32(1):81–95.

Finkelstein, M.M., Jerrett, M. & Sears, M.R. 2005. Environmental inequality and circulatory disease mortality gradients. *Journal of epidemiology and community health*, 59(6):481–487.

FRIDGE. 2004. Study to examine the potential socio-economic impact of measures to reduce air pollution from combustion. Final report submitted to the trade and industry chamber: fund for research into industrial development growth and equity (FRIDGE). Johannesburg: Bentley West Management Consultants.

Giles, L.V., Brauer, M., Barn, P., Künzli, N., Romieu, I., Mittleman, M.A., Van Eeden, S., Allen, R., Carlsten, C., Stieb, D., Noonan, C., Smargiassi, A., Kaufman, J.D., Hajat, S., Kosatsky, T. & Brauer, M. 2011. From good intentions to proven interventions: effectiveness of actions to reduce the health impacts of air pollution. *Environmental health perspective*, 119(1):29–36.

Hammitt, J.K. & Robinson, L.A. 2011. The income elasticity of the value per statistical life: transferring estimates between high and low-income populations. *Journal of benefit-cost analysis*, 2(1):1-27.

Hubbell, B.J., Fann, N. & Levy, J.I. 2010. Methodological considerations in developing local-scale health impact assessments: balancing national, regional, and local data. *Air quality atmosphere and health*, 2009:99–110.

Janssen, N. & Mehta, S. 2006. Human exposure to air pollution. (In World Health Organization, ed. Air quality guidelines: global update 2005. Copenhagen.).

Kan, H., London, S.J., Chen, G., Zhang, Y., Song, G., Zhao, N., Jiang, L. & Chen, B. 2007. Differentiating the effects of fine and coarse particles on daily mortality in Shanghai, China. *Environment international*, 33:376–384.

Kerimray, A., Rojas-Solorzano, M., Torkmahalleh, M., Amouei, M., Hopke, P. & Gallachoir, H. 2017. Coal use for residential heating: patterns, health implications and lessons learned. *Energy for sustainable development*, 40(2017):19–30.

Laden, F., Schwartz, J., Speizer, F.E. & Dockery, D.W. 2006. Reduction in Fine particulate air pollution and mortality. Extended follow-up of the Harvard Six Cities study. *American journal of respiratory and critical care medicine*, 173(6):667–672.

Leiman, A., Standish, B., Boting, A. & van Zyl, H. 2007. Reducing the healthcare costs of urban air pollution: The South African experience. *Journal of environmental management*, 84(1):27–37.

Mathee, A. & Wright, C. 2014. Environmental Health in South Africa. *South African health review*, 2013/2014:105–116.

Mdluli, T.N. 2007. The societal dimensions of domestic coal combustion: people's perceptions and indoor aerosol monitoring. Johannesburg: University of the Witwatersrand. (Thesis – PhD).

Miller, T.R. 2000. Variations between countries in values of statistical life. *Journal of transport, economics and policy*, 34(2):169–188.

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.

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(7):782–790.

OECD (Organisation for Economic Co-operation and Development). 2011. Valuing mortality risk reductions in regulatory analysis of environmental, health and transport policies: policy implications. Paris.

Ou, C., Hedley, A.J., Chung, R.Y., Thach, T., Chau, Y., Chan, K., Yang, L., Ho, S., Wong, C. & Lam, T. 2008. Socioeconomic disparities in air pollution-associated mortality. *Environmental research*, 107(2008):237–244.

Pascal, M., Corso, M., Ung, A., Declerq, C. & Medina, S. 2011. Improving knowledge and communication for decision making on air pollution and health in Europe (Aphekom): guidelines for assessing the health impacts of air pollution in European cities. Saint-Maurice: French institute for public health surveillance.

Peters, A. & Pope, C.A. 2002. Cardiopulmonary mortality and air pollution. *Lancet*, 360(9341):1184–1185.

Pope, 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(2006):709–742.

Raghunandan, A., Matooane, M. & Oosthuizen, R. 2008. Impacts of air pollution. Publication series b: book 5. Pretoria: Department of Environmental Affairs.

Rollin, H. 2017. Editorial evidence for health effects of early life exposure to indoor air pollutants: what we know and what can be done. *Clean Air Journal*, 27(1):2-3.

Scorgie, Y., Burger, L.W. & Sowden, M. 2001. Assessing the potential of low-smoke fuels in addressing air pollution and human health impacts due to household coal burning emissions. *The clean air journal*, 10(8):6–16.

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. *The clean air journal*, 13(2):5–18.

Smith, K.R., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z., Dherani, M., Hosgood, H.D., Mehta, S., Pope, D. & Rehfuess, E. 2014. Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. *Annual review of public health*, 35(1):185–206.

South Africa. Department of Environmental Affairs. 2004. National Environmental Management: Air Quality Act (39 of 2004). *Government gazette*, 27318:2-56.

South Africa. Department of Environmental Affairs. 2012. Highveld priority area air quality management plan: executive summary. Pretoria.

StatsSA (Statistics South Africa). 2014. General Household Survey, 2013. Statistical release: P0318. https://www.statssa.gov.za/publications/P0318/P03182013.pdf Date of access: 20 Oct. 2017.

Sustainable Energy Africa. 2014. Tackling urban energy poverty in South Africa. Cape Town.

Tyson, P.D. & Preston-Whyte, R.A. 2012. The Weather and Climate of Southern Africa. 2nd ed. Cape Town: Oxford University Press.

U.S. EPA. (United States Environmental Protection Agency). 2012. Provisional assessment of recent studies on health effects of particulate matter exposure. North Carolina, Research Triangle Park.

Van Niekerk, W. 2006. From technology transfer to participative design: a case study of pollution prevention in South African townships. *Journal of energy in Southern Africa*, 17(3):58–63.

Von Schirnding, Y., Bruce, N., Smith, K., Ballard-Tremeer, G., Ezzati, M. & Lvovsky, K. 2002. Addressing the impact of household energy and indoor air pollution on the health of the poor: implications for policy action. Paper prepared for the commission on macroeconomics and health. Geneva: World Health Organization.

WHO (World Health Organization). 2001. Quantification of the health effects of exposure to air pollution. Copenhagen.

WHO (World Health Organization). 2006. Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulphur dioxide. Global update 2005: summary of risk assessment. Geneva.

WHO (World Health Organization). 2013. Health effects of ambient particulate matter. Copenhagen.

WHO (World Health Organization). 2014. WHO guidelines for indoor air quality: household fuel combustion. Geneva.

World Bank Group. 2017. World Bank open data. https://data.worldbank.org/?year_low_desc=true Date of access: 17 Oct. 2017.

Wright, C.Y. & Diab, R. 2011. Air pollution and vulnerability: solving the puzzle of prioritization. *Journal of environmental health*, 73(6):56–64.

CHAPTER 5 - MANUSCRIPT 3

Estimating the regional health and economic benefits of an intervention to reduce residential solid fuel burning on the Highveld

Abstract

Emissions from residential solid fuel burning in densely populated low-income settlements is a significant source of air pollution over the Highveld. The area is densely populated and highly industrialized, resulting in high concentrations of pollutants over the area. Although emissions from industrial sources are much larger, exposure to household emissions poses the most significant risk to human health, as pollutants are emitted at low levels where human exposure is at its highest and where people spend most of their time. The recently published air quality offset guidelines mention emissions from residential solid fuel burning as a possible source to be included in offset programmes. Several pilot offset programmes have been implemented in densely populated low-income areas on the Highveld, but quantifying their true impact remains a challenge. There seems to be consensus however, that the health impacts of interventions should be quantified and used as a measure of their effectiveness and suitability for large-scale roll-out. This paper aimed to estimate the health and associated economic benefits of the large-scale implementation of thermal insulation as intervention measure in low-income settlements on the Highveld in order to provide a more holistic view of the potential impact on the regional scale. We used a land use type regression model and the small area level dataset from the 2011 census to model pre-intervention $PM_{2.5}$ concentrations over the Highveld and identify enumeration areas where population exposure to household emissions was likely to be high. Sampled post-intervention air quality data from a pilot offset programme was used to create a control scenario where we related changes in air quality to changes in avoided premature mortalities in all identified enumeration areas. We estimate that the large-scale implementation of this intervention could result in 143 avoided premature mortalities in our study population. The total estimated economic benefit of the avoided mortalities for the region was just under ZAR (2011) 371 million.

Keywords: Air quality offsets, Household air pollution; Emission controls; Health effects/risks; Human exposure

5.1   Introduction

Residential solid fuel burning in densely populated low-income settlements is a significant source of ambient air pollution in South Africa. The Department of Environmental Affairs (DEA) (2009:vii)

considers the human health impacts associated with residential solid fuel burning to be South Africa's "most serious and pressing air pollution problem". Although more than 85% of South Africans have access to electricity in their homes, many low-income households still supplement their energy needs by burning solid fuels like coal, wood and dung for cooking and space heating (StatsSA, 2017). Rapid urbanisation has also lead to the growth of informal settlements where basic services such as the provision of electricity and waste removal are lacking and severely backlogged, urging residents to use alternative energy sources (Scorgie *et al*., 2003). Exposure to household air pollution (HAP) poses a significant risk to human health, as pollutants are emitted at low levels where human exposure is at its highest and where people spend most of their time. The use of solid fuels, when as widespread as in South Africa, also contributes significantly to ambient air pollution levels and thus causes health impacts far from the original source (Bruce *et al*., 2015; Smith *et al*., 2014; Ezzati & Kammen, 2002).

Current epidemiological evidence link exposure to HAP to diseases such as acute lower respiratory infections (ALRI), chronic obstructive pulmonary disease (COPD), lung cancer, cancer of the nasopharynx and larynx, tuberculosis, perinatal diseases and low birthweight, eye diseases and cataracts, cardiovascular disease and stroke (Ezzati & Kammen, 2002; Brook *et al*., 2010; Smith *et al*., 2014). This burden of disease is not distributed equally amongst or within countries and communities; the brunt of this burden rests on the world's poor, and vulnerable populations like women, children, the elderly and sickly are by far the worst affected. Currently, more than half of deaths due to pneumonia in children under five can be attributed to HAP (Forouzanfar *et al.*, 2015; WHO, 2015a).

Despite efforts by government to improve living conditions, the residents of low-income settlements in South Africa are still living in conditions of extreme poverty, with less access to quality basic services like healthcare, electricity, sanitation and education (MacLean, 2005). These social determinants strongly impact health, as health is influenced by the environment (physical, social and cultural) where people live and not only by behaviour or lifestyle choices (Quigley *et al*., 2006). Epidemiological evidence links various factors with higher susceptibility to air pollution related health impacts. These include factors such as pre-existing cardiovascular or respiratory diseases, diabetes, medication use, age, race and gender. Socioeconomic factors known to influence susceptibility include socioeconomic status, income level, availability of healthcare, housing characteristics and level of educational attainment (Pope & Dockery, 2006). Currently, urban growth in South Africa is occurring mostly in areas of existing poverty, and thus it can be expected that poverty- and environment- related factors will increasingly impact health in urban areas (Mathee & Wright, 2014).

Harmful pollutants emitted include low-level fine particulate matter ($PM_{2.5}$), sulphur dioxide, carbon monoxide, benzene and greenhouse gasses (carbon dioxide and methane). Strong evidence shows $PM_{2.5}$ to be the pollutant of greatest concern to human health, as fine particles can penetrate deep into the lungs where toxins can be absorbed into the bloodstream. Long term exposure to $PM_{2.5}$ is strongly linked with premature cardiovascular and respiratory mortality as well as increased risk of developing lung cancer, cardio pulmonary disease and stroke (Brook *et al.*, 2010; Kan *et al.*, 2007). Worldwide, $PM_{2.5}$ is considered to serve as a general indicator of the anthropogenic pollution mix of concern and is also most frequently used in health risk assessments as a marker for pollution (Ostro, 2006). $PM_{2.5}$ is also the pollutant of focus for this study.

The DEA recognises that it is important to address the environmental injustice of inequitable air pollution exposure through air quality management (AQM) and poverty alleviation (DEA, 2009). The National Environmental Management: Air Quality Act (no 39 of 2004) (NEMAQA) provides the framework for effective and integrated air quality management in the country, and includes a variety of tools and regulations to achieve its objectives (DEA, 2004). The National Ambient Air Quality Standards (NAAQS) were implemented specifically to protect the health of all South Africans, for example. It remains a challenge to manage emissions from non-industrial sources like residential solid fuel burning, as the mandate to address them lie across various government departments (DEA, 2016). A recent development in AQM is the publication of Air Quality Offset Guidelines, where residential solid fuel burning is specifically named as a potential target source.

It is hoped that offset programmes may "provide an opportunity to address complex pollution sources by allowing concerted efforts by both government and polluting industries to clean up the air" (DEA, 2016:7). The guidelines define offsets in the AQM context as "*an intervention, or interventions, specifically implemented to counterbalance the adverse and residual environmental impact of atmospheric emissions in order to deliver a net ambient air quality benefit within, but not limited to, the affected air shed where ambient air quality standards are being or have the potential to be exceeded*" (DEA, 2016:13).

Key principles of offsetting outlined in the guidelines include that an outcome based approach should be used when offsets are implemented, monitored and evaluated. Thus, the focus should be on overall improvements in ambient air quality within the air shed - other positive outcomes and outputs must be of secondary consideration (DEA, 2016). Offsets should also not be "like for like", and should address pollutants with high ambient concentrations, not necessarily pollutants emitted in high concentrations from a specific facility (DEA, 2016). In other words, an offset should counterbalance the environmental impacts of a pollutant from one source by decreasing emissions from another source that has an equivalent impact (Garland *et al.*, 2016).

Langerman *et al.* (2016) propose that offsets aimed at reducing residential emissions should target the largest local source of emissions within an area. Careful consideration should thus be given when deciding which measures should be implemented where. Widespread residential coal burning is a large source of PM$_{2.5}$ emissions in the HPA, whilst it is not such a significant source in the VTAPA or coastal areas, for example. Interventions at the household level can be aimed at reducing the need for solid fuel use by providing access to cleaner fuels, reducing the need for heating through better home insulation or by providing households with more efficient heating/cooking devices. Community scale interventions should target significant local non-household sources that affect air quality in the area (e.g. waste burning).

The implementation of air quality offsets programmes has been a requirement of some Atmospheric Emission Licenses (AEL) since April 2015 and several pilot offset programmes aimed at reducing emissions from solid fuel burning have been implemented in low-income settlements. A few challenges and shortcomings were identified during the course of these projects, some regarding the implementation of offsets and others regarding quantifying the impacts of interventions. (Burger & Piketh, 2016; Garland *et al.*, 2016; Langerman *et al.*, 2016).

The offset guidelines clearly state that any approved offset must be measurable and scientifically robust (DEA, 2016), but to date, no offsets have been implemented at a large scale, thus very limited data exist on how much any proposed intervention would reduce non-industrial emissions (Langerman *et al.*, 2016). Determining the equivalence of the impacts of two sources that may vary significantly in terms of their characteristics also remains a challenge. Accounting approaches that are defensible and scientifically robust are needed to calculate the scale of implementation needed as well as the potential impacts that offsetting could have (Garland *et al.*,2016). The discussion about offset accounting remains a theoretical one at the moment, as offsetting has not passed the pilot stage in South Africa (Langerman *et al.*, 2016). More data is needed in order to identify the most suitable interventions for large-scale roll-out. The consensus seems however, that the health impacts of interventions should be quantified as a measure of both their effectiveness, and suitability for large scale implementation.

This study aims to address this need by estimating the health and associated economic benefits of the regional roll-out of thermal insulation as intervention measure in low-income settlements on the Highveld. To reach this aim, we conducted a health impact assessment using monitored air quality data and other inputs considered to be good predictors of population exposure to HAP.

5.2   Study area

The Highveld region of South Africa is an extensive interior plateau that occupies the largest portion of land area in the country. Much of the industrial and economic activity of the country is found here,

due to the presence of abundant coal fields and other mineral resources. The availability of relatively cheap coal and an (initially) adequate water supply resulted in the area being designated as an area for the establishment of power stations. There are currently 11 operating power stations in the region (Lourens *et al*., 2012). As a result, heavy industry is also clustered in the larger urban centres of the area and include smelters for various metals and petrochemical plants in Secunda and Sasolburg (Scheifinger & Held, 1997). The area is also densely populated and household fuel burning for cooking and heating purposes contributes significantly to poor air quality in the region. Meteorological conditions in the area lead to an accumulation and re-circulation of pollutants, mainly due to the prevalence of a subtropical high that lead to weak pressure gradients and the formation of inversion layers that limit the vertical dilution of pollutants (Wenig *et al*., 2002).
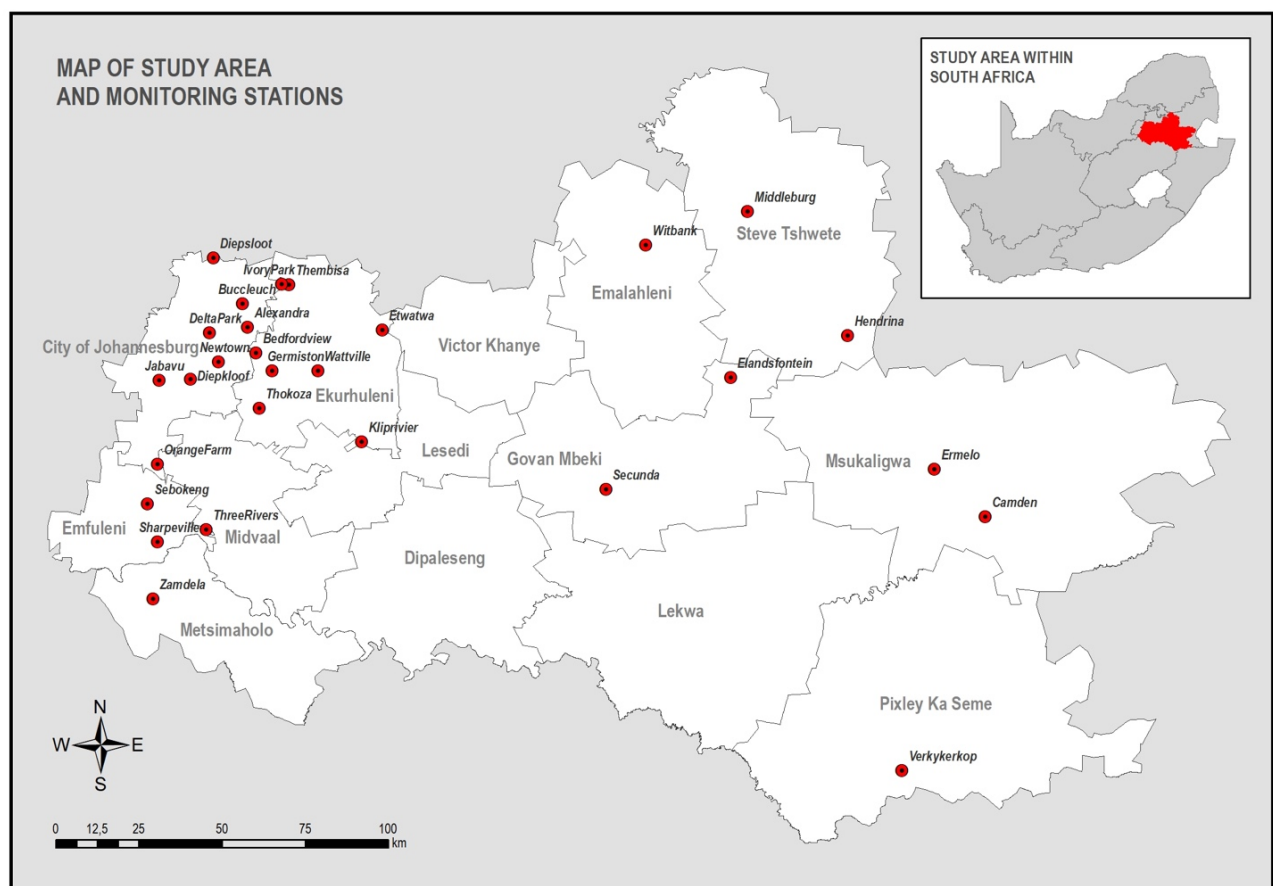
Figure 5-1: Study area and monitoring stations.

The study area includes two priority air quality management areas declared in terms of Section 18(1) of NEMAQA. The Vaal Triangle Air shed Priority Area (VTAPA) was the first priority area to be declared in South Africa in 2006 due to elevated pollutant concentrations within the area (DEAT, 2008). The Highveld Priority Area (HPA) was declared by the minister in 2007, for the same reasons

(DEA, 2012). As both these priority areas overlap provincial boundaries (Free State, Gauteng and Mpumalanga), NEMAQA mandates the DEA as the "lead agent" in the management of these areas (DEA, 2012).

The study area is delineated along the administrative boundaries of the local municipalities within each priority area. Within the VTAPA there are 4 municipalities in two provinces (Free State and Gauteng) and within the HPA, 10 municipalities in two provinces (Gauteng and Mpumalanga). The total population count of all areas included in the study area at the last complete census in 2011 was 10 134 241. Figure 5-1 indicates the location of the study area in South Africa.

5.3   Data and methods

Health impact assessments use data from available epidemiological studies and routine environmental and health data to estimate the impacts of air quality on the health of a given population. This study takes a predictive approach, as it aims to assess the future health impact of a specific intervention measure. This approach does require making assumptions about future trends involving the study population, health outcomes, the time required to achieve decrease pollutant levels as well when health outcomes will occur (Pascal, 2011). Assumptions made in this study will be discussed in the appropriate sections below.

A variety of tools exist to aid analysts, but the majority use the same inputs and process to relate changes in air quality to health outcomes in a particular population (Ostro, 2006). To better fit the context of this study and the high spatial resolution required to most accurately estimate exposure to $PM_{2.5}$ from residential solid fuel burning, we used the small area level census dataset to deploy a land use type ordinary least squares model. This model provided estimates of mean $PM_{2.5}$ concentrations that was used together with the census data to identify areas where health benefits associated with reduced residential solid fuel burning could be expected. The HIA was then conducted in these identified areas, using the well-established health impact function approach (Broome *et al.*, 2015; Fann *et al.*, 2012) represented by the equation below:

$$\Delta Y = Y_0 \left(1 - e^{\beta \Delta PM}\right) * Pop$$

In the context of this study, **ΔY** represents the change in the number of premature all-cause mortalities; **Y0** the baseline all-cause mortality incidence; **β** the risk coefficient (concentration-response function) derived from epidemiological studies; ΔPM the change in PM exposure after implementation of the intervention ($\mu g\ m^{-3}$) and **Pop** the size of the exposed population. The following sections will discuss the data and methods used to derive each of these required inputs.

5.3.1   Air quality data

Air quality data is a key input for HIA. In order to calculate the health effects of improvements in air quality two datasets are needed. Firstly, baseline air quality conditions where emissions have not yet been controlled need to be established. These baseline conditions are then used as a reference scenario against which to compare the intervention or control scenario (Fann *et al*., 2012).

5.3.1.1   Baseline scenario

Baseline scenarios can be derived from model based estimates, monitored air quality data or a combination of both. To reduce the influence of atypical years or seasons, it is recommended that data used to create the baseline scenario should be based on several recent years of complete data (Ostro, 2006; Abt Associates Inc., 2012).

Various methods were considered to create a representative baseline scenario including the use of a refined dispersion model like CALPUFF or a comprehensive air quality model like CAMx. Both models offer considerable benefits including the consistent spatial distribution of the variable of interest and the ability to model basic (CALPUFF) and advanced (CAMx) chemical processes such as secondary particle generation. These models require detailed emissions inventories and meteorological data to run, however. This, along with the fact that neither model was designed for near ground, high resolution modelling made them unsuitable for this study.

As mentioned above, most modelling efforts currently do not provide enough certainty for emissions that contribute to ambient air quality in low-income settlements. For HIA in low-income areas, the high spatial- and low temporal variability of annual PM concentrations need to be presented as accurately as possible, as these areas house a significant portion of South African society. Areas located just outside low-income areas typically show less spatial variability on the annual time frame (Burger & Piketh, 2016). Monitoring data is the only reliable way to do this, despite the limitations of limited monitoring sites and high spatial variability in the study area. For these reasons, a land use type ordinary least squares regression, using available monitoring data was chosen to create the baseline $PM_{2.5}$ concentrations for this study.

Monitoring data for PM_{10} and $PM_{2.5}$ were obtained from the South African Air Quality Information System (SAAQIS). Data were requested for all monitoring stations in the study area from 1998 to 2016. Figure 5-1 indicates the locations and names of monitoring sites used in this study. 17 of the 30 monitoring stations used are situated in densely populated low-income settlements, seven in low density residential areas, two in areas with heavy urban traffic, one at a power station, one in a rural area and one in the CBD of Johannesburg. The raw datasets were merged and processed into a final dataset. An automated quality control (QC) was performed and problematic values were

flagged. Flagged data was inspected manually to determine the validity of the potential problems. The data for any problem periods were set to missing. Table 5-1 provides a summary of the land use type, data availability and data retention after QC for each monitor station used in the study.

Table 5-1: Monitoring data used to estimate baseline PM$_{2.5}$ concentrations in the study area.

Monitor Site	Land use type	Data % available	Data % after QC	Number of days	Start date	End date
Newtown	CBD	67	99	2440	2004-07-31	2012-09-30
Alexandra	High density low-income	31	45	772	2004-01-01	2010-10-31
Diepkloof	High density low-income	80	95	2718	2007-02-05	2012-09-30
Diepsloot	High density low-income	41	79	272	2009-03-24	2012-09-30
Ermelo	High density low-income	90	98	2526	2008-09-01	2012-09-30
Etwatwa	High density low-income	87	98	448	2011-05-03	2012-09-30
Hendrina	High density low-income	66	99	1857	2008-09-01	2012-09-30
Ivory Park	High density low-income	43	89	432	2009-07-27	2012-09-30
Jabavu	High density low-income	74	100	2161	2004-07-14	2012-09-30
Mokopane	High density low-income	87	100	932	2012-09-01	2012-09-30
OrangeFarm	High density low-income	61	92	2273	2004-05-14	2012-09-30
Sebokeng	High density low-income	79	97	2611	2007-02-21	2012-09-30
Secunda	High density low-income	77	94	2140	2008-09-01	2012-09-30
Sharpeville	High density low-income	87	100	2859	2007-05-17	2012-09-30
Thembisa	High density low-income	81	100	519	2011-01-01	2012-09-30
Thokoza	High density low-income	76	100	459	2011-01-05	2012-09-30
Wattville	High density low-income	90	100	439	2011-06-01	2012-09-30
Zamdela	High density low-income	64	95	2083	2007-05-17	2012-09-30
DeltaPark	Low density residential	64	88	1647	2004-07-31	2012-09-30
Germiston	Low density residential	80	100	489	2011-01-01	2012-09-30
Kliprivier	Low density residential	82	92	2747	2007-02-09	2012-09-30
Lephalale	Low density residential	57	95	623	2011-01-01	2012-09-30
Middleburg	Low density residential	82	100	2487	2008-01-01	2012-09-30
Thabazimbi	Low density residential	60	100	807	2012-10-01	2012-09-30
Witbank	Low density residential	87	100	2438	2008-09-01	2012-09-30
Camden	Power station	81	100	885	2011-01-01	2012-09-30
Verkykerkop	Rural	94	100	629	2012-02-29	2012-09-30
Bedfordview	Urban Traffic	90	100	382	2011-08-01	2012-09-30
Buccleuch	Urban Traffic	62	95	2251	2004-07-31	2012-09-30

5.3.1.1.1 Model deployment

To avoid overfitting data and covariance between variables it was decided to use only a few independent variables that represent the important drivers of ambient air quality in low-income settlements.

Data from the 2011 Census were used for this part of the analysis. Enumeration areas (EA) were chosen for the scale of analysis as these EAs are the smallest geographical areas into which the country is divided for census (also called the 'small area level dataset'). The census dataset includes a large number of housing and household goods and services related statistics, including energy/fuel use, access to basic services and type of dwelling (Statistics South Africa, 2012). The underlying philosophy of this approach is very similar to that of Wright and Diab (2011), who also used census data to better represent the socio-economic factors that play such an important role in exposure and vulnerability to adverse health impacts in this context.
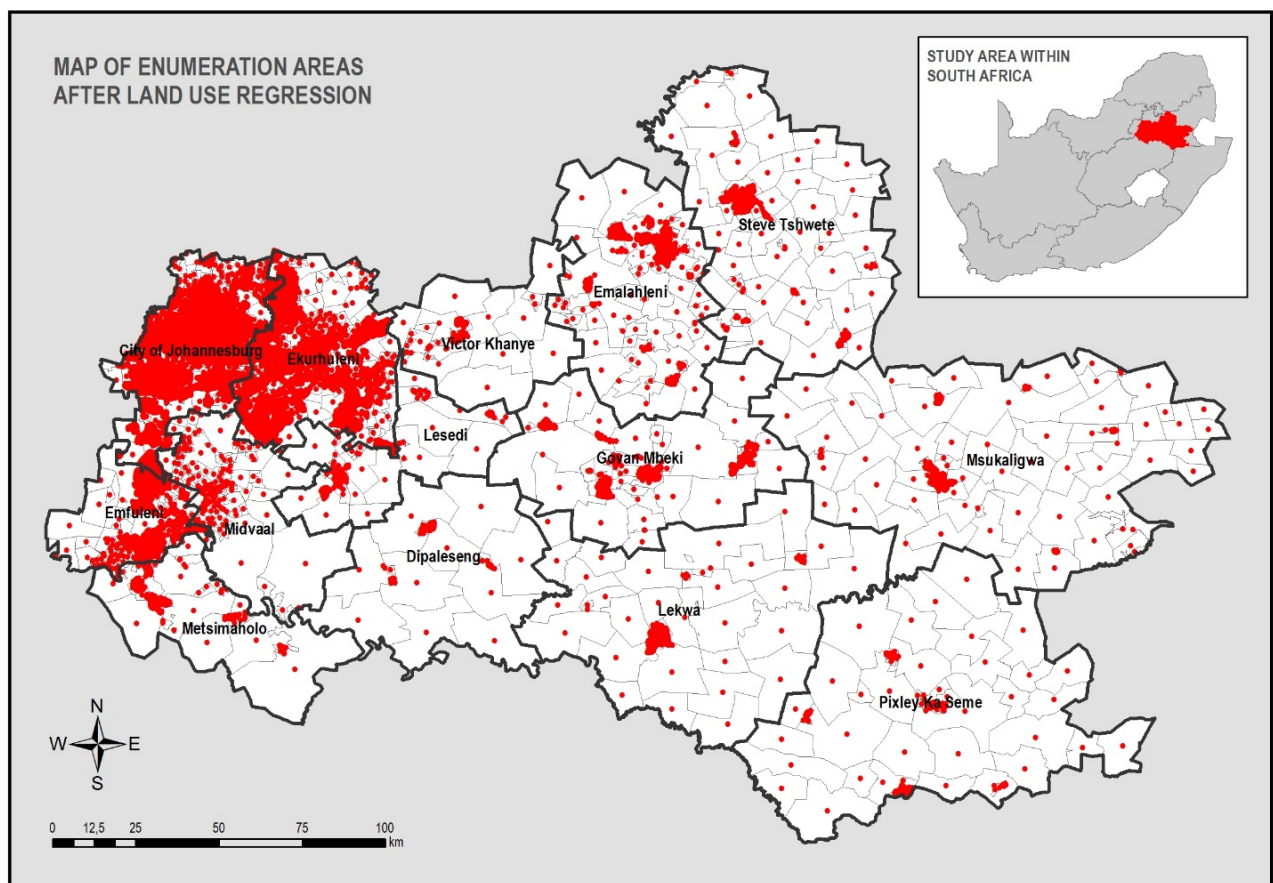
Figure 5-2: Map of numeration areas after land use regression.

For the purposes of this study PM_{10} was used as the dependent variable. The following three independent variables were used:

1. Percentage of households using "dirty" fuels for cooking, heating or lighting in each EA.

2. Percentage of informal households in each EA.

3. Population density in each EA.

The model was trained using the variables obtained from the different sources within a 250m radius of each of the available monitoring stations and the EA layer of the 2011 census data used to deploy the model. Figure 5-2 shows how this method filled the "gaps" in air quality data relative to the population in the study area.

PM_{10} concentrations were converted to $PM_{2.5}$ using a conversion factor of 0.5. This conversion factor is recommended for use in urban areas of developing countries by the WHO (2006). This rate was also assumed by Norman *et al.* (2007) in areas where no monitored data were available to calculate an actual rate. To test the suitability of 0.5 as conversion factor, we used data from sampling campaigns conducted in three townships within the borders of the study area (KwaDela, Zamdela and Emalahleni) to calculate a representative average $PM_{2.5}/PM_{10}$ ratio. The average conversion factors for the combined datasets was 0.47, very close to the chosen factor of 0.5. Mean annual PM_{10} and $PM_{2.5}$ concentrations for each monitoring station are shown in Figure 5-3.
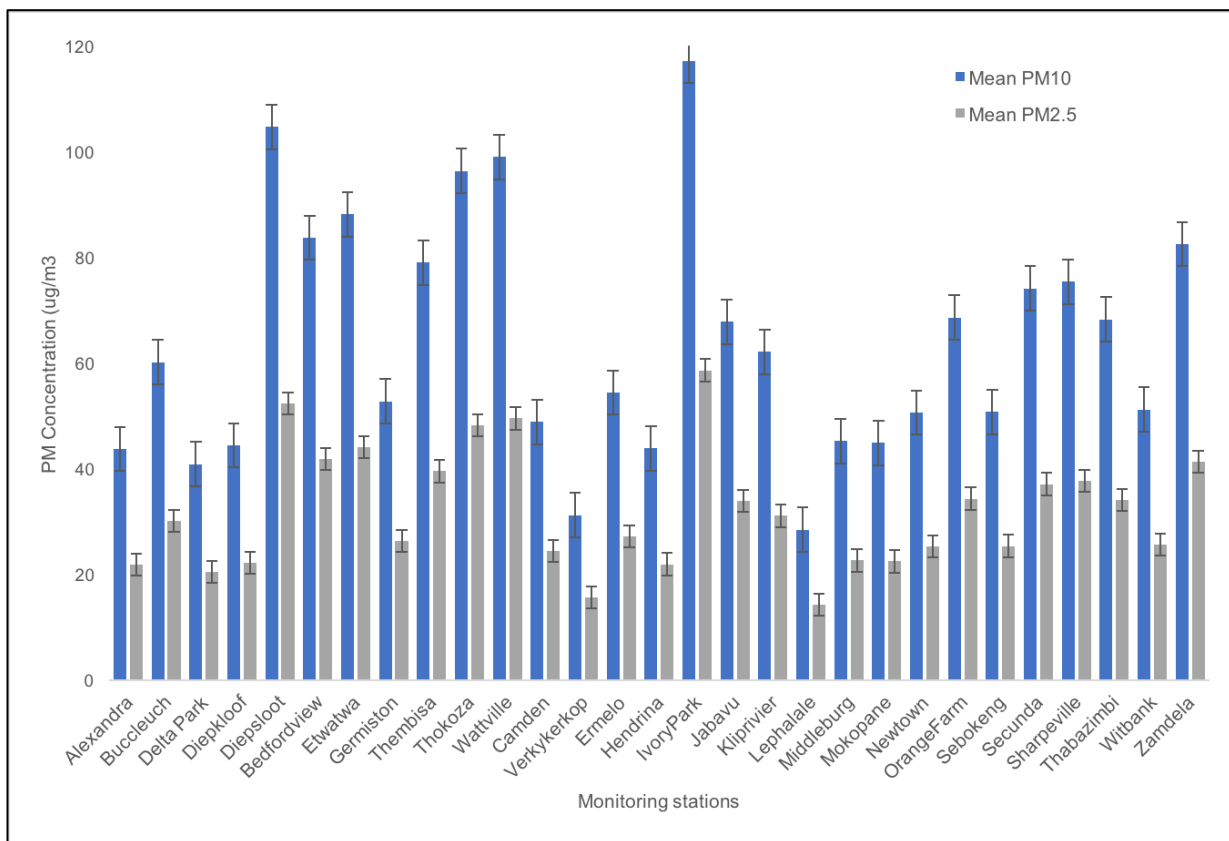
Figure 5-3: Mean annual PM concentrations by monitoring station

5.3.1.2   Control Scenario

The control scenario in a modelling study "is a sensitivity scenario in which emissions from one or more source sectors are changed (increased or decreased) from a given baseline scenario" (Abt Associates Inc., 2012:2-4) The control scenario generally represents air quality levels after a new policy has been implemented, in this case, the implementation of thermal insulation as intervention measure.

In order to most accurately represent the context of the study, findings from a pilot air quality offset project in the community of KwaDela were used to estimate post intervention air quality improvements. This project is discussed in detail elsewhere (Lindeque, Burger & Piketh, 2016 - Manuscript 2). The next section will briefly discuss the KwaDela project, followed by a discussion on how findings were incorporated and used in the context of this larger study.

The township of KwaDela lies within the administrative borders of the Msukaligwa local municipality. The community of KwaDela is very representative of low-income settlements on the Highveld in terms of household size, age and sex ratios, annual household income and employment status. KwaDela was chosen as the project site because of these population characteristics, along with its geographic location far from industrial and other urban sources, small population size (total population of 3786) and high levels of dependence on solid fuel burning for cooking and space heating.

The project involved a pre-intervention sampling campaign in the cold and warm seasons of 2013-2014, followed by the retrofitting of 505 houses with thermal insulation from February to June 2014, and a post-intervention sampling campaign in the cold and warm months of 2014 and early 2015.

The standard deviation of sampled $PM_{2.5}$ concentrations in KwaDela was on the same order of magnitude as the mean. This large variability would make it difficult to detect relatively small decreases due to better thermal insulation. In this case, we used the difference between the two observed pre- and post- intervention means (4 $\mu g/m^3$) to estimate the effect the intervention had on ambient air quality in KwaDela (using Cohen's *d*). For this campaign, the difference did not obtain statistical significance (*d*=0.6).

The aim of this study was to estimate the health and economic benefits that the large-scale implementation of thermal insulation could have on the Highveld. Therefore, the difference between the means of the two sampling campaigns was used as the control value. The control value of 4 μgm^3 was applied to all EAs where more than 10% of households reported using dirty fuels as an energy source for either lighting, cooking or heating. $PM_{2.5}$ concentrations in areas where less than 10% of households reported using dirty fuels were left unchanged. Δ values in the control dataset

were thus either 0 $\mu g/m^3$ or 4 $\mu g/m^3$, in order to estimate health benefits of air quality improvements in only those areas where dirty fuels were used.

5.3.1.3   Choice of concentration-response function

Concentration-response functions (CRF) are derived from epidemiological studies and represent the statistical relationship between a certain adverse health effect and ambient air pollution concentrations. The choice of health outcomes to include in an assessment is largely based on available evidence from epidemiological and scientific literature and the availability of data regarding baseline incidence rates. To be truly representative, incidence rates should ideally be collected at the place and scale of assessment (e.g. city, province, local municipality) and should match the age cohort being studied (Ostro, 2006).

This study aims to establish the long-term health and economic benefits of thermal insulation as an air pollution intervention measure in low-income settlements. Therefore, only long-term benefits associated with improved air quality was included in this analysis. In order to minimise double-counting the health effects of reduced $PM_{2.5}$ concentrations, our analysis was limited to the impacts of reduced $PM_{2.5}$ emissions on premature all-cause mortality, as reliable morbidity and hospital admission records are difficult to collect in South Africa. No long-term epidemiological studies to establish local CRFs have been conducted in South Africa (Norman *et al*., 2007) and therefore, the most suitable CRF had to be identified from the current literature.

To estimate the impacts of reduced $PM_{2.5}$ on premature all-cause mortality, we chose the CRF from the extended analysis of the ACS cohort study by Krewski *et al*. (2009) due to the statistical power of a cohort study spanning 35 years. Their risk estimate for all-cause mortality (Table 5-2) was calculated using a random effects Cox model that controlled for seven ecological and 44 individual covariates, based on average exposure levels for over 116 U.S. cities.

Table 5-2: Risk estimate from Krewski *et al*., 2009

Health outcome	Population	Risk estimate (%) (95% CI)
Premature all-cause mortality	$\geq$ 30 years	RR=1.06 (1.03 -1.09) per 10 ug/m³ increase in $PM_{2.5}$

5.3.2   Population data and baseline all-cause mortality incidence

Population data from the 2011 census was used at the EA level to establish the number of people exposed in each area. Using data at such a high spatial resolution is needed in order to take the high spatial variably in population densities and living conditions that influence population exposure to HAP into account. The census dataset provides an age breakdown of the population in each EA

and thus it was possible to calculate the population aged ≥30 for each EA, to better match the CRF (Krewski *et al*., 2009) chosen for this study.

A baseline mortality rate is needed in order to estimate the average number of people that died in the study population over a certain period of time due to all causes including air pollution (Abt Associates Inc., 2012). Mortality by cause of death statistics for 2011 were obtained at the local municipality level from Statistics South Africa. Data were extracted according to the ICD 10 code for main cause of death (ICD 10 A00-Y98) for all deaths that occurred at age ≥30. Remaining data was then sorted according to local municipality of death and the total number of deaths ≥30 for each municipality calculated. The baseline mortality rate for each municipality was then calculated (total population ≥30/total mortality ≥30) to be applied to each EA within the administrative border of each respective municipality. For this study, we assume that the annual birth and mortality rates remain constant at the 2011 count, and that there is no migration. This will result in underestimations of future health benefits, but should still provide a good estimate of the impacts of improved air quality on the study population.

5.3.3   Health impact assessment

All inputs discussed above were applied to each EA on the census 2011 dataset for the study area (n=14 330). The health impact for each small area was then calculated using the equation discussed above.   Health impacts were thus calculated for each EA using site specific air quality data, population numbers and mortality incidence rates. Results for each EA were then sorted by local municipality and summed. In our main analysis, we make the same assumptions as (Broome *et al*., 2015 and Fann *et al*., 2012):

1. We assume the intervention to cause immediate reductions in PM$_{2.5}$ and that this has an immediate impact on health, continuing for 20 years;
2. That all PM$_{2.5}$ related deaths are attributable to exposure to our modelled air quality, occurring over a 20-year period, with the largest number of avoided deaths occurring in the earlier years.

5.3.4   Economic valuation of health benefits

When calculating the economic value of health benefits, we do not calculate the value of an individual life, but rather the sum of all small individual changes in risk (OECD, 2011). For this study, we used the Value of a Statistical Life (VSL) for economic valuation, a widely used method to estimate the economic value of avoided premature mortality (Chanel, 2011; OECD, 2011; U.S. EPA, 2014, 2016). There is currently no standard VSL available for South Africa, thus we adapted the United States Environmental Protection Agency's (U.S. EPA) standard VSL by using the benefits transfer technique. This method was used by Leiman *et al*. (2007) when they evaluated the

economic value of reduced healthcare costs of urban air pollution in South Africa. The benefits transfer technique involves adjusting the VSL from the original study to reflect the differences in income, income growth, inflation and Purchasing Power Parity (PPP) between study areas. Thus, these adjustments reflect changes in real income over time (Hammitt & Robinson, 2011; U.S. EPA, 2014). For this study, the U.S. EPA standard VSL (in US$ 2008) was converted to a 2011 South African Rand (ZAR) value using the following formula:

$$\text{VSL (ZAR 2011)} = \frac{VSL_{US,2008} \left(\frac{Y_{SA,2011}}{Y_{US,2008}}\right)^{elasticity} * PPP_{SA,2008} * CPI_{SA,2011}}{CPI_{SA,2008}}$$

Where **VSL (ZAR 2011)** is the converted VSL value for South Africa in 2013 ZAR; **VSL$_{US, 2008}$** is the VSL value for the United States in 2008 US$; **Y** is the per capita GDP of South Africa and the United States in 2008, expressed in international (Purchasing Power Parity (PPP)-adjusted) dollars and **elasticity** represents the income elasticity of the VSL. In this case we used the U.S. EPA recommended value of 0.40, as well as the more conservative elasticity used by Leiman *et al.* (2007), for comparison purposes. **PPP$_{SA, 2008}$** is the PPP index in 2008 (in units of ZAR per International dollar) and **CPI** represents the consumer price index for South Africa in 2011 and 2008 respectively. All economic data for the US and South Africa were obtained from the World Bank Open Data database (World Bank Group, 2017). The VSL values used in this study are presented in Table 5-3 below.

Table 5-3: VSL for South Africa in ZAR 2011

Study	Elasticity	VSL (ZAR 2011)
U.S. EPA (2014)	0.40	12 363 127
Leiman *et al.* (2007)	1.50	2 597 088

The VSL was multiplied with the avoided premature mortalities calculated in each EA and aggregated at the local municipality level.

5.4 Results and discussion

5.4.1 Air Quality Estimates

A land use type ordinary least squares regression was performed to predict the relationship between variance in PM$_{10}$ concentrations and the population density (POPDENS), percentage of households using dirty fuels (DIRTY) and percentage of informal households (INFORMAL) in each EA. The

mean R^2 (0.815) R^2 shows tthat 85% of PM_{10} variability is related to the population density, % of household using dirty fuels and % of informal households in the study area. The adjusted R^2 (0.790), used to assess the number of predictors included in the analysis, indicates that the number of predictors used in the regression are a good fit. The percentage of informal households showed the strongest positive correlation with PM_{10} concentrations (r=0.45) followed by much weaker positive correlations for percentage of dirty fuels (r=0.0023) and population density (r=0.0021). Model output is summarised in Table 5-4.

Table 5-4: Land use type regression output.

Variable	R	Std error	t	P
CONSTANT	42.5000	3.870	10.996	0.00
DIRTY	0.0023	0.140	0.016	0.98
POPDENS	0.0021	0.000	5.506	0.00
INFORMAL	0.4500	0.092	4.941	0.00

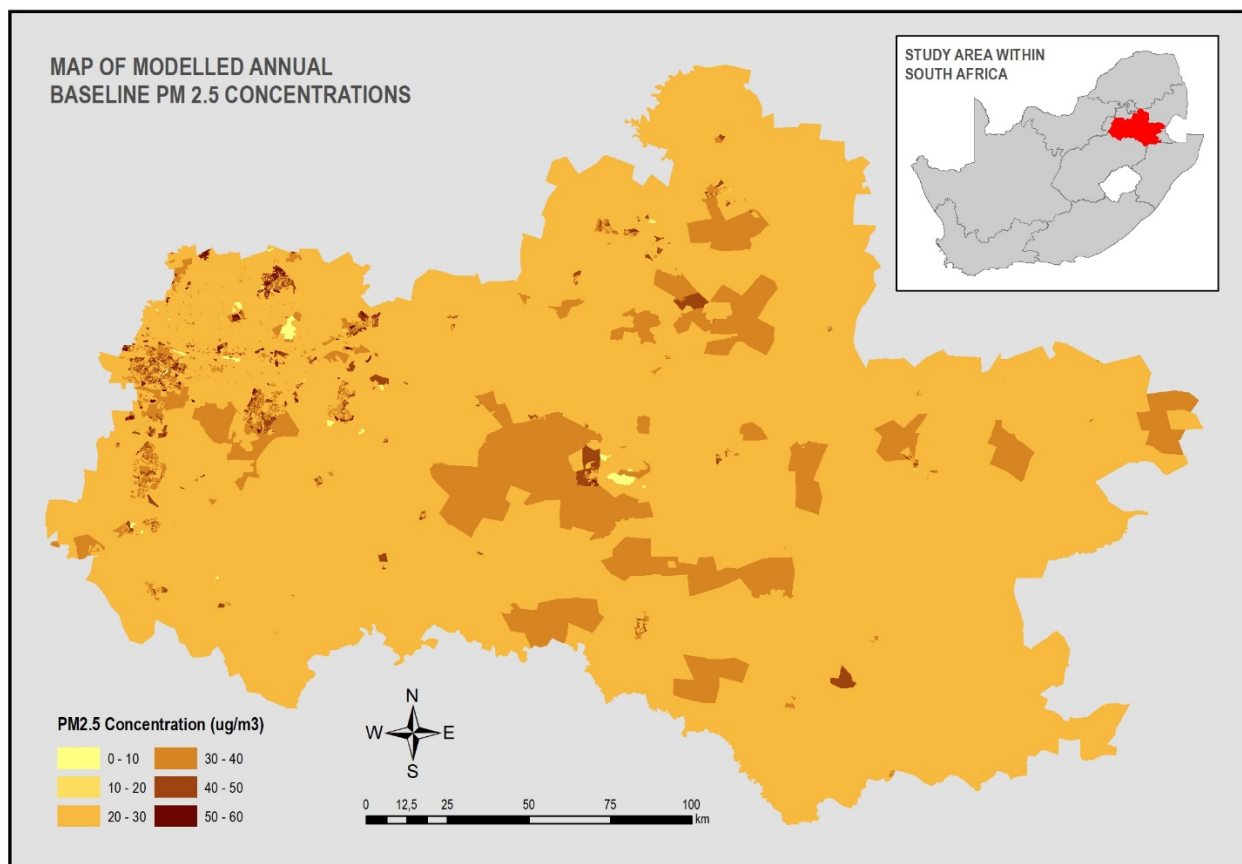The spatial distribution of baseline $PM_{2.5}$ concentrations are show in Figure 5-4.

Figure 5-4: Map of modelled annual baseline $PM_{2.5}$ concentrations

3 056 (n=14 330) EAs were identified as areas where more than 10% of households reported using dirty fuels. This represents 21% of the total EAs within the study area. Municipalities where more than 50% of EAs were identified as suitable control areas include Pixley Ka Seme (92%), Msukaligwa (83%), Victor Khanye (80%), Lekwa (65%), Lesedi (54%), Govan Mbeki (53%) and Steve Tshwete (52%). Much lower percentages of EAs were identified in major urban areas. The lowest percentage recorded was for the City of Johannesburg (6%), followed by Emfuleni (8%) and Ekurhuleni (23%). Overall, populations of municipalities located in the HPA show a much higher reliance on solid fuel burning than those in the VTAPA. Total control areas identified for each municipality are summarised in Table 5-5.

The results of the land use regression model show high spatial variability of $PM_{2.5}$ concentrations over the Highveld (Figure 5-4). This conforms to our current understanding of the high impact of residential solid fuel burning emissions with limited spatial extent during stable conditions. The model does not however show dispersion between source areas and does not accurately represent areas of low concentrations. Most of the area shows typical background $PM_{2.5}$ concentrations of between 20 to 30 $\mu g/m^3$. The spatial variability of modelled baseline concentrations closely matches the population distribution in the area, with highest concentrations in densely populated areas.

5.4.2   Estimates of avoided $PM_{2.5}$ mortalities and related economic benefits

We estimate that reducing $PM_{2.5}$ exposure by 4 $\mu g/m^3$ in the identified 21% of EAs on the Highveld will result in 143 (95% CI: -52 – 276) avoided premature deaths over 20 years. It is important to note that these deaths are not avoided altogether, but only deferred to the future. The economic benefits associated with these avoided premature mortalities are estimated to be just under ZAR (2011) 1. 8 Billion (0.4 elasticity) and ZAR (2011) 380 Million (1.5 elasticity). This large difference in estimates reiterates the need for careful consideration of the study context when using the benefits transfer technique. We believe the conservative estimate by Leiman *et al.* (2007) to be more representative in the context of this study. All further discussions of economic benefits will thus refer to estimates calculated using their chosen elasticity of 1.5. A summary of economic valuations for both elasticities can be found in Table 5-5.The spatial distribution of health and economic benefits are illustrated in Figure 5-5.

The metropolitan municipality of Ekurhuleni would benefit the most from air quality improvements in low-income settlements, with an estimated 49 avoided premature mortalities. The economic benefit of these avoided deaths is estimated to be just under ZAR (2011) 120 Million. Ekurhuleni is densely populated (1609 persons/km^2) and 22.6% of the population lived in informal housing in 2011. Although 82% of the population have access to electricity, 23% of the EAs within the city were identified as areas where solid fuel burning could cause air quality problems. All these factors are shown to impact air quality in our regression analysis.

Table 5-5: Summary of results.

| Municipality	Total no. of EAs per municipality	No. of EAs included in HIA per municipality (% of total)	Avoided premature mortalities	Avoided premature mortalities	Economic benefits (U.S. EPA, 2014)	Economic benefits (Leiman et al., 2007)
			Central estimate	95 % CI	(ZAR 2011)	(ZAR 2011)
City of Joburg	5 800	315 (6%)	11	-4 - 21	136 247 839	28 621 206
Dipaleseng	76	58 (18%)	2	-1 - 3	19 689 516	4 136 122
Ekurhuleni	4 610	1 051 (23%)	49	-17 - 89	568 764 414	119 478 764
Emalahleni	457	239 (53%)	9	-3 - 18	115 773 265	24 320 169
Emfuleni	1 136	111 (10%)	6	-2 - 11	68 732 804	14 438 510
Govan Mbeki	455	239 (53%)	11	-4 - 20	130 612 726	27 437 453
Lekwa	194	127 (65%)	8	-3 - 15	93 214 267	19 581 263
Lesedi	187	101 (54%)	13	-5 - 26	166 329 800	34 940 440
Metsimaholo	260	76 (30%)	3	-1 - 6	35 990 299	7 560 382
Midvaal	184	68 (37%)	2	-1 - 4	22 598 560	4 747 217
Msukaligwa	259	214 (83%)	13	-5 - 25	157 708 991	33 129 491
Pixley Ka Seme	132	121 (92%)	8	-3 - 15	97 988 907	20 584 258
Steve Tshwete	458	239 (52%)	5	-2 - 9	59 783 136	12 558 478
Victor Khanye	122	97 (80%)	8	-3 - 15	94 461 707	19 843 309
Grand Total	**14 330**	**3 056 (21%)**	**143**	**-52 - 276**	**1 767 896 230**	**371 377 016**
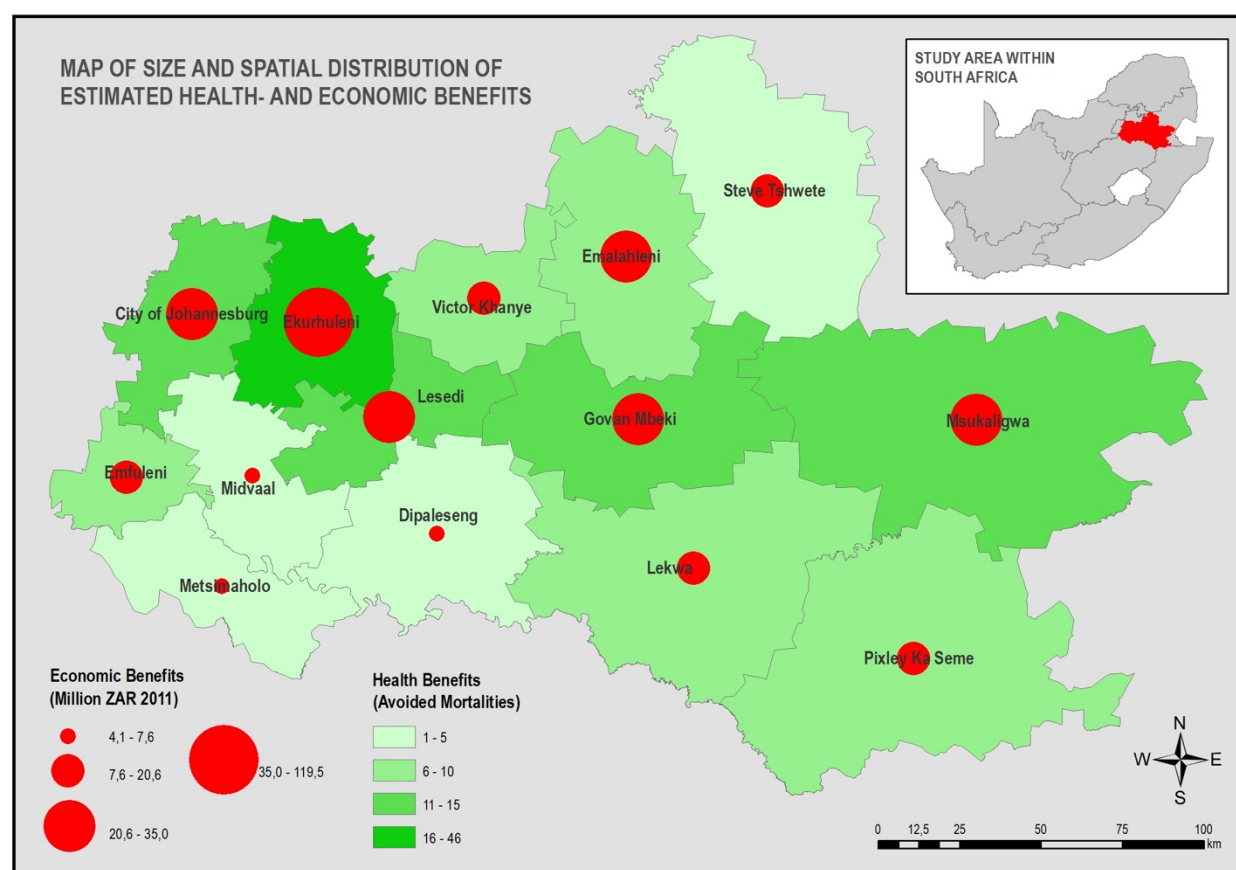
Figure 5-5: Size and spatial distribution of estimated health and economic benefits.

Estimates for the only other metropolitan municipality in the study area, City of Johannesburg, is significantly lower (11 avoided premature mortalities valued at ZAR 2011 28.7 million), despite the fact that the city is the most densely populated area in South Africa at 2696 persons/km^2. In this municipality, 90.8% of the population have access to electricity and 81,4% live in formal housing (StatsSA, 2017). Only 6% of EAs within the administrative boundaries of Johannesburg were identified as areas where more than 10% of households reported using dirty fuels. The contrast between the two major metropolitan areas highlights the important role than living conditions have in determining public health and population exposure.

The municipalities with the second highest estimated health benefits are Lesedi and Msukaligwa, both situated in the HPA. 13 avoided premature mortalities were predicted for each municipality. The combined economic benefits of these 26 avoided deaths were estimated to be just over ZAR (2011) 68 million.

Overall, both municipalities are sparsely populated, Msukaligwa at 25 persons/km^2 and Lesedi at 67 persons km^2, but in certain EAs population densities were much higher. Wesselton, a township outside Ermelo in Msukaligwa, is very densely populated with 14 689 persons/km^2, for example. This high spatial variability again highlights the need to use population data at the highest spatial resolution available for HIA in this context.

Large parts of the population in both these municipalities are reliant on solid fuel burning to supplement their energy needs: 54% of EAs in Lesedi and 83% of EAs in Msukaligwa were identified for inclusion in the HIA. The reliance on solid fuels in Msukaligwa could be due to the fact that only 75% of the population in Msukaligwa had access to electricity, and 25% of the population lived in informal dwellings in 2011 (StatsSA, 2017). The municipality is also located close to the Mpumalanga coal fields, and coal is thus widely available as a cheaper alternative fuel source. The population of Lesedi is smaller than that of Msukaligwa by almost 50 000 people and 90% of the population had access to electricity in 2011, yet the health benefits for both municipalities are estimated to be the same. This could be ascribed to higher overall population density in Lesedi. All other results of the HIA and economic valuation are summarised by municipality in Table 5-5.

5.4.3   Limitations of this study

Transferring the health impacts and economic valuations calculated for populations in developed countries onto our study population introduces considerable uncertainty to our results. The demographic profile, socio-economic conditions and pollutant mix in our study population and area differ considerably from the population used by Krewski *et al*. (2009) to derive the CRF used in this study. The Integrated Exposure Response (IER) functions developed for the Global Burden of Disease (GBD) assessment could provide better estimates. The IERs were developed for cause

specific morbidity and mortality (Smith *et al*., 2014). Since the scope of this study included all-cause mortality to avoid double counting attributable mortalities, these IERs were not used.

Assumptions made that population growth-, death and migration rates remained steady at the 2011 rates, could also result in an underestimation of the health benefits assumed to occur over 20 years. These results should thus be interpreted as a relatively conservative estimate.

Limited monitored air quality data available for the study area could lead to the over or underestimation of population exposure. Since 17 out of the 30 monitoring stations used to estimate baseline air quality were situated in densely populated low-income settlements, we believe the data to be representative of exposure levels in our study population.

5.5   Conclusion

Emissions from residential solid fuel burning is a significant source of air pollution in South Africa. It is also a difficult source to manage, and affects the health of millions of vulnerable South Africans. Air quality offsets aimed at reducing these emissions could be a valuable tool to help manage the problem and improve the quality of life of low-income households. Offsetting is only at the pilot stage in the country and information about the impacts of the large-scale roll-out of interventions are needed to identify the most suitable and cost effective offset options. This study estimated the health and associated economic benefits of the large-scale implementation of thermal insulation as intervention measure on the Highveld, in order to better inform decision making about the suitability for large scale implementation in the future. Two priority air quality management areas are included in the study area and modelled baseline $PM_{2.5}$ concentrations show that the annual NAAQS for $PM_{2.5}$ are frequently exceeded in both areas.

The impact of household emissions on ambient air quality is problematic to assess, due to the high spatial variability between areas of high concentration. A land use regression model was deployed using the small area level census dataset in order to more accurately estimate the spatial variation in mean annual $PM_{2.5}$ concentrations over the area. Estimates of mean $PM_{2.5}$ concentrations were used together with the census data to identify areas where reduced residential solid fuel burning could decrease population exposure. A health impact assessment was then conducted in these identified areas, using the well-established health impact function approach.

The use of spatially representative baseline ambient PM concentrations, population densities, incidence data and delta (control) values provided a more representative analysis scenario, to assess the impact of the intervention in only those areas where it would likely be implemented. Overall, populations of municipalities located in the HPA show a much higher reliance on solid fuel burning than those in the VTAPA. The HPA could thus be a better area for large-scale roll out of

thermal insulation as part of air quality offset programs. Results indicate that reducing $PM_{2.5}$ concentrations in areas where residents burn solid fuels by 4 ug/m^3 would result in an estimated 143 avoided premature mortalities. The economic value of these benefits was estimated to be ZAR (2011) 370.1 Million. Despite the limitations and large assumptions that need to be made at during the HIA process, we believe that it could be a valuable tool to help identify areas where interventions would be most effective.

5.6   References

Abelson, P. 2008. Establishing a monetary value for lives saved: issues and controversies, working papers in cost-benefit analysis. (*In* Delivering better quality regulatory proposals through better cost-benefit analysis: Conference hosted by the Office of Best Practice Regulation, 21 November 2007. Sydney: Department of Finance and Deregulation).

Abt Associates Inc. 2012. BenMAP environmental benefits mapping and analysis program: user's manual. Prepared for the Office of Air Quality Planning and Standards U.S. Environmental Protection Agency. North-Carolina: Research Triangle Park.

Ackerman, F. & Heinzerling, L. 2002. Pricing the priceless: cost-benefit analysis of environmental protection. *University of Pennsylvania law review*, 150(5):1553.

Altieri, K.E. & Keen, S. 2016. BENMAP as a tool for analysing the health benefits of reductions in ambient air pollution in South Africa. (*In* Beyond air quality. Annual conference hosted by National Association for Clean Air (NACA), Mbombela, 5-7 Oct. 2016.).

Anenberg, S.C., Belova, A., Brandt, J., Fann, N., Greco, S., Guttikunda, S., Heroux, M.E., Hurley, F., Krzyzanowski, M., Medina, S., Miller, B., Pandey, K., Roos, J. & Van Dingenen, R. 2016. Survey of ambient air pollution health risk assessment tools. *Risk analysis*, 36(9):1718–1763.

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., Thomas, E. & Bruce, N. 2009. Household energy, indoor air pollution and child respiratory health in South Africa. *Journal of energy in Southern Africa*, 20(1):4–13.

Boldo, E., Linares, C., Aragonés, N., Lumbreras, J., Borge, R., De la Paz, D., Pérez-Gómez, B., Fernández-Navarro, P., García-Pérez, J., Pollán, M., Ramis, R., Moreno, T., Karanasiou, A. & López-Abente, G. 2014. Air quality modelling and mortality impact of fine particles reduction policies in Spain. *Environmental research*, 128(2014):15–26.

Brauer, M., Freedman, G., Frostad, J., Van Donkelaar, A., Martin, R.V, Dentener, F., Van Dingenen, R., Estep, K., Amini, H., Apte, J.S., Balakrishnan, K., Barregard, L., Broday, D.M., Feigin, V., Ghosh, S., Hopke, P.K., Knibbs, L.D., Kokubo, Y., Liu, Y., Ma, S., Morawska, L., Texcalac Sangrador, J.L., Shaddick, G., Anderson, H.R., Vos, T., Forouzanfar, M.H., Burnett, R.T. & Cohen, A. 2016. Ambient air pollution exposure estimation for the global burden of disease 2013. *Environmental science and technology*, 50(1):79–88.

Brook, R.D., Rajagopalan, S., Pope, 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. *Circulation*, 121(21):2331–2378.

Broome, R.A., Fann, N., Navin, T.J., Fulcher, C., Duc, H. & Morgan, G.G. 2015. The health benefits of reducing air pollution in Sydney, Australia. *Environmental research*, 143(2015):19–25.

Bruce, N., Pope, D., Rehfuess, E., Balakrishnan, K., Adair-Rohani, H. & Dora, C. 2015. WHO indoor air quality guidelines on household fuel combustion: strategy implications of new evidence on interventions and exposure–risk functions. *Atmospheric environment*, 106(2015):451–457.

Cairncross, E.K. 2016. The state of South Africa's air quality monitoring network, and its air quality. (*In* Beyond air quality. Annual conference hosted by National Association for Clean Air (NACA), Mbombela, 5-7 Oct. 2016.).

Cao, J., Yang, C., Li, J., Chen, R., Chen, B., Gu, D. & Kan, H. 2010. Association between long-term exposure to outdoor air pollution and mortality in China: a cohort study. *Journal of hazardous materials*, 186(2-3):1594–1600.

Casper, S. 2008. Using EPA's environmental benefits mapping and analysis program (BenMAP) for global health impact analysis. Chapel Hill: University of North Carolina.

Chanel, O. 2011. Guidelines on monetary cost calculations related to air-pollution health impacts: Aphekom project - deliverable D6. Marseilles: Aphekom.

Daly, A. & Zannetti, P. 2007. An introduction to air pollution – definitions, classifications, and history. (*In* Zannetti, P., Al-Ajmi, D. & Al-Rashied, S., *eds*. Ambient air pollution. Fremont: The EnviroComp Institute.).

DEA *see* South Africa. Department of Environmental Affairs.

DEAT *see* South Africa. Department of Environmental Affairs and Tourism.

Diab, R.D., Muller, E. & Matooane, M. 2006. Application of health risk assessment models to South African conditions. *South African geographical journal*, 88(2):159–165.

Ding, D., Zhu, Y., Jang, C., Lin, C.J., Wang, S., Fu, J., Gao, J., Deng, S., Xie, J. & Qiu, X. 2016. Evaluation of health benefit using BenMAP-CE with an integrated scheme of model and monitor data during Guangzhou Asian Games. *Journal of environmental science (China)*, 42(2016):9–18.

DOE *see* South Africa. Department of Energy.

Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G. & Egami, R.T. 2002. The comparison of source contributions from residential coal and low-smoke fuels, using CMB modelling, in South Africa. *Environmental science policy*, 5(2002):157–167.

Ezzati, M. & Kammen, D.M. 2002. The health impacts of exposure to indoor air pollution from solid fuels in developing countries: knowledge, gaps, and data needs. *Environmental health perspective*, 110(11):1057–1068.

Fann, N., Lamson, A.D., Anenberg, S.C., Wesson, K., Risley, D. & Hubbell, B.J. 2012. Estimating the national public health burden associated with exposure to ambient PM2.5 and ozone. *Risk analysis*, 32(1):81–95.

Feigin, V.L., Roth, G.A., Naghavi, M., Parmar, P., Krishnamurthi, R., Chugh, S., Mensah, G.A., Norrving, B., Shiue, I., Ng, M., Estep, K., Cercy, K., Murray, C.J.L. & Forouzanfar, M.H. 2016. Global burden of stroke and risk factors in 188 countries, during 1990–2013: a systematic analysis for the Global Burden of Disease study 2013. *Lancet Neurology,* 15(9):913-924.

FRIDGE. 2004. Study to examine the potential socio-economic impact of measures to reduce air pollution from combustion. Final report submitted to the trade and industry chamber: fund for research into industrial development growth and equity (FRIDGE). Johannesburg: Bentley West Management Consultants.

Garland, R.M., Pauw, C.J., Naidoo, M., Burger, R.P., Piketh, S.J., Weston, M., Fischer, T., Langerman, K.E., Oosthuizen, R., Sibiya, B. & Wernecke, B. 2016. Estimating air pollution impacts from offsetting projects: case study of the Kwazamokuhle pilot project. Paper presented at the 2016 Conference of the National Association for Clean Air (NACA), Nelspruit, 5-6 Oct. 2016.

GBD 2013 Risk Factors Collaborators. 2015. Global, regional and national comparative risk assessment of 79 behavioural, environmental/occupational and metabolic risks or clusters of risks in 188 countries, 1990-2013: a systematic analysis for the Global Burden of Disease Study 2013. *Lancet*, 386(10010):2287–2323.

Hammitt, J.K. & Robinson, L.A. 2011. The income elasticity of the value per statistical life: transferring estimates between high and low-income populations. *Journal of benefit-cost analysis*, 2(1):1-27.

Hayes, E. 2017. Commentary: challenging the air quality discourse – people create pollution not technology. *Clean air journal*, 27(1):16-17

Hubbell, B.J., Fann, N. & Levy, J.I. 2010. Methodological considerations in developing local-scale health impact assessments: balancing national, regional, and local data. *Air quality, atmosphere, and health*, 2(2):99–110.

Huber, M., Knottnerus, J.A., Green, L., Van der Horst, H., Jadad, A.R., Kromhout, D., Leonard, B., Lorig, K., Loureiro, M.I., Van der Meer, J.W.M., Schnabel, P., Smith, R., Van Weel, C. & Smid, H. 2011. How should we define health? *British medical journal*, 343(2011):1-3.

Hutton, G. 2011. Air Pollution. Global damage costs of air pollution from 1900 to 2050. Copenhagen: Consensus on human challenges.

Hutton, G. & Rehfuess, E. 2006. Guidelines for conducting cost-benefit analysis of household energy and health interventions. Geneva: World health organization.

Hutton, G., Rehfuess, E. & Tediosi, F. 2007. Evaluation of the costs and benefits of interventions to reduce indoor air pollution. *Energy for sustainable development*, 2007(XI):4.

Kan, H., London, S.J., Chen, G., Zhang, Y., Song, G., Zhao, N., Jiang, L. & Chen, B. 2007. Differentiating the effects of fine and coarse particles on daily mortality in Shanghai, China. *Environment international*, 33(3):376–384.

Keen, S. & Altieri, K.E. 2016. Assessing the health benefits of attaining and strengthening ambient air quality standards in Cape Town. (*In* Beyond air quality. Annual conference hosted by National Association for Clean Air (NACA), Mbombela, 5-7 Oct. 2016.).

Kelly, F.J. & Fussell, J.C. 2012. Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. *Atmospheric environment*, 60(0):504–526.

Kerimray, A., Rojas-Solórzano, L., Torkmahalleh, M.A., Hopke, P.K. & Gallachóir, B.P.Ó. 2017. Coal use for residential heating: Patterns, health implications and lessons learned. *Energy for sustainable development*, 40(2017):19–30.

Khumalo, N. 2016. State of the air report and national air quality indicator. Paper presented at the 11th Air Quality Governance Lekgotla, Mbombela, 3-4 Oct. 2016.

Krewski, D., Jerrett, M., Burnett, R.T., Ma, R., Hughes, E., Shi, Y., Turner, M.C., Pope III, C.A., Thurston, G., Calle, E.E., Thun, M.J., Beckerman, B., DeLuca, P., Finkelstein, N., Ito, K., Moore, D.K., Newbold, K.B., Ramsay, T., Ross, Z., Shin, H. & Tempalski, B. 2009. Extended follow-up and spatial analysis of the American cancer society study linking particulate air pollution and mortality. *Health effects institute*, 140(2009):5-114.

Langerman, K., Wernecke, B., Piketh, S.J., Murray, H., Smith, H., Pauw, C., Snyman, H., Fisher, T. & Weston, M. 2016. Practical considerations in the development of an air quality offsets programme. (In Beyond air quality. Annual conference hosted by National Association for Clean Air (NACA), Mbombela, 5-7 Oct. 2016.).

Leiman, A., Standish, B., Boting, A. & Van Zyl, H. 2007. Reducing the healthcare costs of urban air pollution: the South African experience. *Journal of environmental management*, 84(1): 27–37.

Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., Amann, M., Anderson, H.R., Andrews, K.G., Aryee, M., Atkinson, C., Bacchus, L.J., Bahalim, A.N., Balakrishnan, K., Balmes, J., Barker-Collo, S., Baxter, A., Bell, M.L., Blore, J.D., Blyth, F., Bonner, C., Borges, G., Bourne, R., Boussinesq, M., Brauer, M., Brooks, P., Bruce, N.G., Brunekreef, B., Bryan-Hancock, C., Bucello, C., Buchbinder, R., Bull, F., Burnett, R.T., Byers, T.E., Calabria, B., Carapetis, J., Carnahan, E., Chafe, Z., Charlson, F., Chen, H., Chen, J.S., Cheng, A.T.A., Child, J.C., Cohen, A., Colson, K.E., Cowie, B.C., Darby, S., Darling, S., Davis, A., Degenhardt, L., Dentener, F., Des Jarlais, D.C., Devries, K., Dherani, M., Ding, E.L., Dorsey, E.R., Driscoll, T., Edmond, K., Ali, S.E., Engell, R.E., Erwin, P.J., Fahimi, S., Falder, G., Farzadfar, F., Ferrari, A., Finucane, M.M., Flaxman, S., Fowkes, F.G.R., Freedman, G., Freeman, M.K., Gakidou, E., Ghosh, S., Giovannucci, E., Gmel, G., Graham, K., Grainger, R., Grant, B., Gunnell, D., Gutierrez, H.R., Hall, W., Hoek, H.W., Hogan, A., Hosgood, H.D., Hoy, D., Hu, H., Hubbell, B.J., Hutchings, S.J., Ibeanusi, S.E., Jacklyn, G.L., Jasrasaria, R., Jonas, J.B., Kan, H., Kanis, J. a., Kassebaum, N., Kawakami, N., Khang, Y.H., Khatibzadeh, S., Khoo, J.P., Kok, C., Laden, F., Lalloo, R., Lan, Q., Lathlean, T., Leasher, J.L., Leigh, J., Li, Y., Lin, J.K., Lipshultz, S.E., London, S., Lozano, R., Lu, Y., Mak, J., Malekzadeh, R., Mallinger, L., Marcenes, W., March, L., Marks, R., Martin, R., McGale, P., McGrath, J., Mehta, S., Mensah, G. a., Merriman, T.R., Micha, R., Michaud, C., Mishra, V., Hanafiah, K.M., Mokdad, A. a., Morawska, L., Mozaffarian, D., Murphy, T., Naghavi, M., Neal, B., Nelson, P.K., Nolla, J.M., Norman, R., Olives, C., Omer, S.B., Orchard, J., Osborne, R., Ostro, B., Page, A., Pandey, K.D., Parry, C.D.H., Passmore, E., Patra, J., Pearce, N., Pelizzari, P.M., Petzold, M., Phillips, M.R., Pope, D., Pope, C.A., Powles, J., Rao, M., Razavi, H., Rehfuess, E. a., Rehm, J.T., Ritz, B., Rivara, F.P., Roberts, T., Robinson, C., Rodriguez-Portales, J. a., Romieu, I., Room, R., Rosenfeld, L.C., Roy, A., Rushton, L., Salomon, J. a., Sampson, U., Sanchez-Riera, L., Sanman, E., Sapkota, A., Seedat, S., Shi, P., Shield, K., Shivakoti, R., Singh, G.M., Sleet, D. a., Smith, E., Smith, K.R., Stapelberg, N.J.C., Steenland, K., Stöckl, H., Stovner, L.J., Straif, K., Straney, L., Thurston, G.D., Tran, J.H., Van Dingenen, R., Van Donkelaar, A., Veerman, J.L., Vijayakumar, L., Weintraub, R., Weissman, M.M., White, R. a., Whiteford, H., Wiersma, S.T., Wilkinson, J.D., Williams, H.C., Williams, W., Wilson, N., Woolf, A.D., Yip, P., Zielinski, J.M., Lopez, A.D., Murray, C.J.L. & Ezzati, M. 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions,

1990-2010: a systematic analysis for the global burden of disease study 2010. *Lancet*, 380(9859):2224–2260.

Lourens, A.S.M., Butler, T.M., Beukes, J.P., Van Zyl, P.G., Beirle, S., Wagner, T.K., Heue, K.-P., Pienaar, J.J., Fourie, G.D. & Lawrence, M.G. 2012. Re-evaluating the NO2 hotspot over the South African Highveld. *South African journal of science*, 108(11/12):83–91.

MacLean, S.J. 2005. Human security as 'freedom from want': inequities and health in South Africa. *Policy and society*, 24(1):48–72.

Mathee, A. & Wright, C. 2014. Environmental health in South Africa. (In Padarath, A. & English, R. eds. South African Health Review 2013/14. Durban: Health Systems Trust.).

Matooane, M. & Diab, R. 2011. Why we need to manage air quality. Publication series: book 4. Pretoria: Department of Environmental Affairs.

Mehta, S. & Shahpar, C. 2004. The health benefits of interventions to reduce indoor air pollution from solid fuel use: a cost-effectiveness analysis. *Energy for sustainable development*, VII(3):53–59.

Mekwa, N,J., Madela-Mntla, E,N., Loots, G., Van Niekerk, A., Jeenah, M. & Mayosi, B,M. 2016. The development of a National Health Research Observatory in South Africa: considerations and challenges. (*In* Padarath, A., King, J., Mackie, E. & Casciola, J. *eds*. South African Health Review 2016. Durban: Health Systems Trust.).

Miller, T.R. 2000. Variations between countries in values of statistical life. *Journal of transport, economy and policy*, 34(2):169–188.

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.

Naiker, Y., Diab, R.D., Zunckel, M. & Hayes, E.T. 2012. Introduction of local air quality management in South Africa: overview and challenges. *Environmental science and policy*, 17(2012):62–71.

Norman, R., Cairncross, E., Witi, J. & Bradshaw, D. 2007. Estimating the burden of disease attributable to urban outdoor air pollution in South Africa in 2000. *South African medical journal*, 97(2007):782–790.

OECD (Organisation for Economic Co-operation and Development). 2003. Glossary of statistical terms - Indoor air pollution (definition). https://stats.oecd.org/glossary/detail.asp?ID=1336 Date of access: 9 Aug.2017.

OECD (Organisation for Economic Co-operation and Development). 2011. Valuing mortality risk reductions in regulatory analysis of environmental, health and transport policies: policy implications. Paris: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). 2016. Policy highlights: the economic consequences of outdoor air pollution. Paris: OECD Publishing.

Pascal, M. 2011. Improving knowledge and communication for decision making on air pollution and health in Europe. Guidelines for assessing the health impacts of air pollution in European cities. Saint-Maurice: French Institute for Public Health Surveillance.

Pascal, M., Corso, M., Chanel, O., Declercq, C., Badaloni, C., Cesaroni, G., Henschel, S., Meister, K., Haluza, D., Martin-Olmedo, P. & Medina, S. 2013. Assessing the public health impacts of urban air pollution in 25 European cities: results of the Aphekom project. *Science of the total environment*, 449(2013):390–400.

Pascal, M., Corso, M., Ung, A., Declerq, C. & Medina, S. 2011. Improving knowledge and communication for decision making on air pollution and health in Europe (Aphekom): guidelines for assessing the health impacts of air pollution in European cities. Saint-Maurice: French institute for public health surveillance.

Peters, A. & Pope, C.A. 2002. Cardiopulmonary mortality and air pollution. *Lancet*, 360(9341):1184–1185.

Pope, 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(2006):709–742.

Pope, C.A., Turner, M.C., Burnett, R.T., Jerrett, M., Gapstur, S.M., Diver, W.R., Krewski, D. & Brook, R.D. 2015. Relationships between fine particulate air pollution, cardiometabolic disorders, and cardiovascular mortality. *Circulation research*, 116(1):108-115.

Quigley, R., Den Broeder, L., Furu, P., Bond, A., Cave, B. & Bos, R. 2006. Health impact assessment: international best practice principles. Special publication series no. 5. Fargo: International Association for Impact Assessment.

Raghunandan, A., Matooane, M. & Oosthuizen, R. 2008. Impacts of air pollution. Publication series b: book 5. Pretoria: Department of Environmental Affairs.

Reiss, R., Anderson, E.L., Cross, C.E., Hidy, G., Hoel, D., McClellan, R. & Moolgavkar, S. 2007. Evidence of health impacts of sulfate-and nitrate-containing particles in ambient air. *Inhalation toxicology*, 19(5):419–449.

Rollin, H. 2017. Editorial evidence for health effects of early life exposure to indoor air pollutants: what we know and what can be done. *Clean air journal*, 27(1):2–3.

Scheifinger, H. & Held, G. 1997. Aerosol behaviour on the South African Highveld. *Atmospheric environment*, 31(21):3497–3509.

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(2):5–18.

Scott, V., Schaay, N., Schneider, H. & Sanders, D. 2017. Addressing social determinant of health in South Africa. *South African health review*, 20(2017):77-88.

Smith, K.R., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z., Dherani, M., Hosgood, H.D., Mehta, S., Pope, D. & Rehfuess, E. 2014. Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. *Annual review of public health*, 35(1):185–206.

Solar, O. & Irwin, A. 2010. A conceptual framework for action on the social determinants of health. Social determinants of health discussion paper 2. Geneva: World Health Organization.

South Africa. Department of Energy. 2013. A survey of energy related behaviour and perceptions in South Africa: the residential sector. Pretoria.

South Africa. Department of Environmental Affairs. 2004. National Environmental Management: Air Quality Act (39 of 2004). *Government gazette*, 27318:2-56.

South Africa. Department of Environmental Affairs. 2009. National Ambient Air Quality Standards. *Government gazette*, 32816:6–9.

South Africa. Department of Environmental Affairs. 2009. State of air report 2005. A report on the state of the air in South Africa. Pretoria.

South Africa. Department of Environmental Affairs. 2012. Highveld priority area air quality management plan: executive summary. Pretoria.

South Africa. Department of Environmental Affairs. 2016. National Environmental Management Act (107 of 1998): air quality offsets guideline. *Government gazette*, 39833:8-28.

South Africa. Department of Environmental Affairs and Tourism. 2007. Discussion Document: the establishment of national standards for ambient air quality. Pretoria.

South Africa. Department of Environmental Affairs and Tourism. 2008. Executive summary of the Vaal Triangle Airshed priority area air quality management plan. *Government gazette*, 31615:4–39.

Stanek, L.W., Sacks, J.D., Dutton, S.J. & Dubois, J.J.B. 2011. Attributing health effects to apportioned components and sources of particulate matter: An evaluation of collective results. *Atmospheric environment*, 45(2011):5655–5663.

StatsSA (Statistics South Africa). 2012. Census 2011: metadata. http://www.statssa.gov.za/census/census_2011/census_products/Census_2011_Metadata.pdf Date of access: 20 Oct. 2017.

StatsSA (Statistics South Africa). 2014. General Household Survey, 2013. Statistical release: P0318. https://www.statssa.gov.za/publications/P0318/P03182013.pdf Date of access: 20 Oct. 2017.

StatsSA (Statistics South Africa). 2017. Statistics by place. http://www.statssa.gov.za/?page_id=964 Date of access: 20 Oct. 2017.

Terblanche, A.P., Nel, C.M. & Tosen, G.R. 1995. Respiratory health impacts of three electrification scenarios in South Africa. *Journal of energy in Southern Africa*, 6(2):93–96.

U.S. EPA (United States Environmental Protection Agency). 2011. The benefits and costs of the Clean Air Act from 1990 to 2020: summary report. Washington.

U.S. EPA (United States Environmental Protection Agency). 2012. Provisional Assessment of Recent Studies on Health Effects of Particulate Matter Exposure. North Carolina: Research Triangle Park.

U.S. EPA (United States Environmental Protection Agency). 2014. Guidelines for preparing economic analyses. Washington.

U.S. EPA (United States Environmental Protection Agency). 2016. Valuing mortality risk reductions for policy: a meta-analytic approach. Washington.

Van Niekerk, W. 2006. From technology transfer to participative design: a case study of pollution prevention in South African townships. *Journal of energy in Southern Africa*, 17(3):58–63.

Von Schirnding, Y., Bruce, N., Smith, K., Ballard-Tremeer, G., Ezzati, M. & Lvovsky, K. 2002. Addressing the impact of household energy and indoor air pollution on the health of the poor: implications for policy action and intervention measures. Paper prepared for the commission on macroeconomics and health. Geneva: World Health Organization.

Voorhees, A.S., Wang, J., Wang, C., Zhao, B., Wang, S. & Kan, H. 2014. Public health benefits of reducing air pollution in Shanghai: a proof-of-concept methodology with application to BenMAP. *Science of the total environment*, 485–486:396–405.

Wenig, M., Spichtinger, N., Stohl, A., Held, G., Beirle, S., Wagner, T., Jähne, B. & Platt, U. 2002. Intercontinental transport of nitrogen oxide pollution plumes. *Atmospheric chemistry and physics discussion*, 2(2002):2151–2165.

WHO (World Health Organization). 2006. Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: global update 2005: summary of risk assessment. Geneva.

WHO (World Health Organization). 2013. Health effects of ambient particulate matter. Copenhagen.

WHO (World Health Organization). 2014. Guidelines for indoor air quality: household fuel combustion. Geneva.

WHO (World Health Organization). 2015a. World Health Assembly closes, passing resolutions on air pollution and epilepsy. http://www.who.int/mediacentre/news/releases/2015/wha-26-may-2015/en/ Date of access: 28 May 2015.

WHO (World Health Organization). 2015b. Health and the environment: addressing the health impact of air pollution. Report by the secretariat for the sixty-eighth World Health Assembly. Agenda 68/18. Item 14.6. Geneva. http://apps.who.int/gb/ebwha/pdf_files/WHA68/A68_18-en.pdf. Date of access: 22 Jun. 2016.

WHO (World Health Organization). 2016. Health in the post-2015 development agenda: need for a social determinants of health approach. Joint statement of the UN Platform on Social Determinants of Health Background. Geneva.

Wichmann, J. & Voyi, K.V. 2006. Influence of cooking and heating fuel use on 1-59 month old mortality in South Africa. *Maternal and child health journal*, 10(6):553-561

Wright, C. & Oosthuizen, R. 2002. Air quality monitoring and evaluation tools for human health risk reduction in South Africa. http://www.ehrn.co.za/download/air_quality_monitoring.pdf Date of access: 17Oct. 2017.

Wright, C.Y. & Diab, R. 2011. Air pollution and vulnerability: solving the puzzle of prioritization. *Journal of environmental health*, 73(6):56–64.

CHAPTER 6

CONCLUSIONS

Long term exposure to air pollution is associated with increased risk of respiratory, cardio- and cerebrovascular morbidity and mortality as well as acute effects like skin and eye irritations. The negative health impacts of air pollution also place a significant economic burden on affected individuals, their families, the public healthcare system and the economy of a country. Some populations are more vulnerable to these health impacts due to factors like pre-existing conditions, age, gender, place of residence and socio-economic status. In South Africa, residents of densely populated low-income settlements are frequently exposed to concentrations of air pollution that exceed the NAAQS. Residential solid fuel burning for cooking and heating is a significant source of emissions in these settlements, as many residents rely on solid fuels to supplement their energy needs.

Interventions aimed at reducing these emissions could improve health outcomes and reduce their associated economic costs. Residential solid fuel burning is mentioned as a possible source to include in air quality offset programmes, and a number of pilot projects have been implemented in low-income settlements on the Highveld. These projects have only been implemented at the community scale and more information is needed to identify interventions suitable for large scale implementation. Estimating the health and associated economic benefits of interventions could improve our understanding of the true impact, cost effectiveness and sustainability of different types of interventions and provide a more holistic approach to aid decision making.

This study aimed to estimate the health and economic benefits of the regional implementation of thermal insulation as intervention measure in low-income settlements on the Highveld. This aim was achieved by firstly investigating the relevant physical and socio-economic variables needed to conduct a health and economic impact assessment in the South African context. Next, the pre-and post-intervention $PM_{2.5}$ concentrations over the Highveld were quantified in order to estimate the size and spatial distribution of health and economic benefits associated with reduced $PM_{2.5}$ concentrations in low-income settlements on the Highveld. The following sections will discuss the major findings of this study as they pertain to each research objective and corresponding manuscript.

6.1   Relevant inputs needed for HIA in the South African context

The objective of the first paper titled *"Health impact assessment of interventions to reduce residential solid fuel burning: challenges and considerations"* was to investigate and evaluate the relevant socio-economic and physical variables needed to conduct health and economic impact assessments in the South African context. A literature review was conducted to identify appropriate methodologies and required inputs to conduct the health impact assessment (HIA), followed by an evaluation of the availability and suitability of data needed for use in analyses in the South African context.

The most important findings of this paper include that health impact assessments could offer a more holistic view of the true impacts of air quality interventions in low-income settlements, but that the availability of the required data needed as inputs remains a challenge in the South African context. Inputs needed to conduct HIA on any scale include air pollution concentration and exposure information, population data, background or baseline incidence of mortality and morbidity and appropriate concentration response (C-R) functions. Of all these parameters, only population data was found to be readily available and reliable at all scales. Other needed inputs can be derived from international studies or by converting existing values, but this introduces uncertainties that have to be carefully considered when interpreting results in the South African context.

In manuscript 2 titled "*The health and economic benefits of thermal insulation interventions to improve air quality in a South African township*" the suitability of using a pre-designed software tool for HIA in the South African context is tested. In this paper, the Environmental Benefits Mapping and Analysis Program (BenMAP) developed by the U.S EPA, was used to conduct a health and economic impact assessment of the community scale pilot offset project used as the control scenario in the regional analysis. The main finding of this paper is that even small reductions in $PM_{2.5}$ would result in reduced premature mortality over the long-term, and that the associated economic benefits could outweigh direct intervention implementation costs at the community scale. BenMAP can be used to estimate the health benefits of improved air quality at the community scale, but care should be taken, as the built-in assumptions of the tool were designed for a different context.

The main conclusions that can be drawn from both papers for this research objective are summarised as follows:

- Population exposure to air pollution varies greatly over time and space, both amongst and within countries and communities.
- Low socio-economic status increases vulnerability to the adverse health impacts of air pollution.

- Knowledge regarding the long-term performance and socio-economic benefits of air quality interventions are limited as most studies quantify measures related to fuel consumption and direct emission levels.

- HIA could improve our understanding of the true impact, cost effectiveness and sustainability of different types of interventions and provide a more holistic approach to aid decision making.

- A wide variety of pre-designed software tools are available to conduct HIA.

- Regardless of the method or tool chosen to conduct HIA, it is important that the appropriate geographic scope, resolution and technical rigor are employed for each analysis.

- Main inputs required for HIA are: air pollution concentration and exposure information, population data, background or baseline incidence of mortality and morbidity and appropriate concentration response functions (CRFs).

- Pre- and post-intervention Mean $PM_{2.5}$ concentrations are needed in order to relate changes in air quality to changes in health outcomes in a study population.

- The pollutant of greatest concern in this context is $PM_{2.5}$.

- Monitored $PM_{2.5}$ data are not always available, but $PM_{2.5}:PM_{10}$ ratios can be derived for specific locations to be used in analyses.

- Affordable, up to date and reliable population data is easy to acquire in South Africa.

- The health outcomes most frequently used in HIA include: Cardiovascular mortality, respiratory mortality, all-cause mortality, mortality due to acute respiratory infections (ARI) (children <5), asthma exacerbation, respiratory and cardiovascular hospital visits, acute and chronic bronchitis and decreased lung function.

- Reliable data regarding morbidity and hospital emissions are not readily available and provide limited coverage of different health conditions and geographic areas.

- Applying baseline morbidity rates from original cohort studies to other contexts can add large additional uncertainties, and conducting surveys to ascertain morbidity incidence and prevalence are costly and time consuming.

- Mortality by cause of death statistics are available at various spatial scales, the smallest being the local municipality level. Based on the availability of incidence data, HIAs conducted in South Africa should focus on mortality endpoints.

- The frequency of the occurrence of air pollution related health impacts is very often inversely related to their severity, meaning that the total air pollution related health outcomes in an area are mostly dominated by less severe but more frequent impacts. Including only mortality, the most severe and infrequent health impact of air pollution, represents only the proverbial "tip of the iceberg".

- No long-term epidemiological studies to establish local concentration-response functions have been conducted in South Africa and therefore, the most suitable CRFs have to be identified from epidemiological literature. This introduces further uncertainty into analyses.

- The VSL is commonly used to estimate the economic value of avoided premature mortality.
- As no standard VSL is available for South Africa, the benefits transfer technique should be used when using estimates from other studies.
- Thermal insulation, a source based intervention aimed at reducing the need for solid fuel use, requires very little maintenance or behavioural changes and could thus be a sustainable long-term intervention.

6.2 Spatial variation of pre- and post-intervention PM$_{2.5}$ concentrations

The second research objective, to quantify the spatial variation of pre- and post-intervention PM$_{2.5}$ concentrations in the study area is addressed in manuscript 2 and manuscript 3. In the paper titled "*The health and economic benefits of thermal insulation interventions to improve air quality in a South African township*", sampling data from a community scale intervention is used to estimate the impact that thermal insulation as intervention had on air quality in the community of KwaDela. These results are then used as the control value in the regional analysis described in manuscript 3 titled *"Estimating the regional health and economic benefits of an intervention to reduce residential solid fuel burning on the Highveld"*.

Main findings include that the community scale intervention did not significantly reduce PM$_{2.5}$ concentrations in the community. Small reductions in PM$_{2.5}$ concentrations were however observed during peak heating hours in the colder months. Ambient air quality did not improve enough to comply with the annual NAAQS for PM$_{2.5}$ in KwaDela. Since a statistically significant difference was not observed during the campaign, the difference between the two means of each sampling campaign ($4\mu g/m^3$) was used as the control value in the regional analysis. For the regional scale analysis an ordinary least squares land use type regression using monitored annual PM$_{2.5}$ averages was employed to model the baseline pre-intervention concentrations over the Highveld. The model was deployed on the small area level scale of the census dataset to identify areas where more than 10% of households reported using dirty fuels. The control value ($4\mu g/m^3$ reduction in PM$_{2.5}$) was applied only to these identified areas during the health and economic benefit assessment, to more accurately represent population exposure in the context of this study.

The main conclusions for this research objective are summarised as follows:

- Using monitoring data is the most reliable way to represent the high spatial- and low temporal variability so typical of PM$_{2.5}$ concentrations over the Highveld.
- PM$_{10}$ data is more readily available, but can be converted to PM$_{2.5}$ by using a conversion factor of 0.5.
- The baseline assessment revealed that annual average PM$_{2.5}$ concentrations met the NAAQS in only two of the 30 monitoring stations used in the study.

- Using census data at the smallest available geographical scale (enumeration areas) to deploy land use type regression models provides a more accurate representation of where population exposure from residential solid fuel burning is likely to be high. This can provide a better estimate of the health impacts of interventions that target this specific source, as populations unlikely to be exposed to HAP are excluded from the analysis.

- The presence of informal dwellings was shown to be the best performing predictor of high PM concentrations in an area.

- 21% of enumeration areas in the study area were identified as areas where more than 10% of households reported using dirty fuels. In the control scenario, air quality was "improved" by $4\mu g/m^3$ in only these areas.

- The census data shows that the populations of the three major urban areas in the study area have a lower reliance on solid fuels than peri-urban areas.

6.3   Regional health and economic benefits

The third objective of this study is addressed in manuscript 3 titled *"Estimating the regional health and economic benefits of an intervention to reduce residential solid fuel burning on the Highveld"*. The objective of this paper was to estimate the health and associated economic benefits of the regional roll-out of thermal insulation as intervention measure in low-income settlements on the Highveld.

The well-established health impact function approach was followed to relate the air quality changes estimated in objective two to the populations of the identified enumeration areas. To calculate the economic value of estimated health impacts, the value of a statistical life in (ZAR 2011) was used and multiplied with the number of avoided premature mortalities. The main finding of this paper is that a reduction of $4\mu g/m^3$ in annual average $PM_{2.5}$ concentrations in the 21% of EAs identified as suitable for intervention implementation, could result in an estimated 143 avoided premature deaths over 20 years. The economic value of these avoided deaths was estimated to be 370.1 Million Rand (ZAR 2011). Estimated health and economic benefits showed high spatial variability and a closer analysis of living conditions in EAs where large health benefits were predicted showed that access to electricity, dependence on solid fuels, informal housing and population density had a strong influence on this variability.

The main conclusions for this research objective are summarised as follows:

- Overall, populations of municipalities located in the HPA showed a much higher reliance on solid fuel burning than those in the VTAPA. The highest dependence on solid fuel was in peri-urban areas close to the Mpumalanga coal fields. The HPA could thus be a good area for the large-scale roll-out of offset programs targeting emissions from residential solid fuel burning.

- There are significant differences in health outcome estimates for the two major urban areas within the study area. Estimates for the City of Johannesburg, the largest and most densely populated city in the study area (and South Africa) were significantly lower than those for the city of Ekurhuleni. Better access to electricity, fewer informal settlements and a smaller dependence on solid fuels in Johannesburg could explain this difference.

- The municipalities with the second highest estimated avoided mortalities, Lesedi and Msukaligwa, were located in more sparsely populated peri-urban areas where reliance on solid fuels was high. In both municipalities, the highest estimated health benefits were for EAs with high population densities. The population of Lesedi was smaller than that of Msukaligwa by almost 50 000 people, 90% of the population had access to electricity and yet the health benefits for both municipalities were estimated to be the same. The higher overall population density in Lesedi could be a reason for this result.

- These results support the approach proposed by Wright and Diab (2011): Including indicators of population vulnerability at the EA level can aid analysts in identifying areas where interventions would have the largest health and economic benefits.

- This approach can also help identify specific interventions that would be more effective in different communities by addressing the most manageable cause of poor air quality identified.

6.4 Limitations and assumptions of the study

The approach used for health impact estimations in this study required making assumptions about future trends involving the study population, health outcomes, the time required to achieve decreased pollutant levels as well when health outcomes would occur. It is difficult to accurately project changes in the demographic structure of a population and mortality rates. These assumptions likely resulted in an underestimation of health impacts, but nonetheless introduce less uncertainty than using projected population and mortality data. The main assumptions used in the health impact assessment were:

- That the annual birth and mortality rates remain constant at the 2011 count, and that there will be no migration.

- That the intervention caused immediate reductions in $PM_{2.5}$ and that this has an immediate impact on health, continuing for 20 years.

- That all $PM_{2.5}$ related averted deaths are attributable to exposure to the modelled air quality and pollutant of choice, occurring over a 20-year period, with the largest number of avoided deaths occurring in the earlier years.

Transferring the health impacts and economic valuations calculated for populations in developed countries onto our study population also introduced considerable uncertainty to our results. It is standard practice however to identify appropriate CRFs derived from other studies if none are available for the study population. The large difference in health benefit estimations for the community of KwaDela in the local scale HIA using the CRF from Laden *et al.* (2006) and the regional scale HIA using the CRF from Krewski *et al.* (2009) highlights the impact that the choice of CRF and assessment tool can have on results. The community scale HIA estimated that a $4\mu g/m^3$ reduction in $PM_{2.5}$ concentrations would result in two avoided premature mortalities in contrast to the 0.4 mortalities estimated in the regional scale assessment. There could be several reasons for this large discrepancy:

1) Different study designs, population characteristics and lower pollutant concentrations in the original cohort studies resulted in different relative risk estimates.
2) The built-in assumptions of the BenMAP HIA tool was used to estimate the age specific portion of the population (ages >25) to be included in the analysis, as well as the estimates of the incidence of baseline mortalities (ages>25). Data for all ages were used as inputs and the model estimated the percentage of population to include based on the age structure and mortality incidence of the United States. This included an unrealistic percentage of the KwaDela population in the analysis, as a large number of residents were under the age of 25.
3) The regional scale HIA used age specific population and mortality incidence data (both for ages $\geq$ 30) calculated specifically for each EA. This better represented the age structure of the young population and did not include overestimated baseline mortality incidence.

The uncertainty introduced by using standard VSL estimates from other countries in the South African context is highlighted by the large differences in estimates of economic benefits using different income elasticities. The benefits transfer technique can improve estimates by adjusting values to reflect economic changes over time and space, but careful consideration should be given when choosing the elasticity adjustment.

Limited monitored air quality data available for the study area could lead to the over or underestimation of population exposure.

6.5 Contribution to the current body of knowledge

This study makes a unique contribution to the current body of knowledge by not only using the traditional "what and where" approach in the analysis, but also attempting to include the "who and why" so important to identify vulnerable populations in this context. The results support the approach

proposed by Wright and Diab (2011), that including indicators of population vulnerability at the EA level can aid analysts in identifying areas where interventions would have the largest health and economic benefits. This is currently a challenge in the air quality offset context, and these findings could assist to identify suitable interventions for large scale implementation. The comparison of two modelling approaches aimed at estimating impacts from the same source could also provide better insights into managing uncertainties that assumptions and limitations introduce into the results of analyses.

REFERENCES

Abelson, P. 2008. Establishing a Monetary Value for Lives Saved: Issues and Controversies, Working papers in cost-benefit analysis. Sydney.

Abt Associates Inc 2012. BenMAP Environmental Benefits Mapping nd Analysis Program: User's Manual. Prepared for the Office of Air Quality Planning and Standards U.S Environmental Protection Agency. Research Triangle Park, NC: Abt Associates Inc.

Ackerman, F. & Heinzerling, L. 2002. Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection. Univ. PA. *Law Rev.*, 150:1553.

Altieri, K.E. & Keen, S. 2016. BENMAP as a tool for analysing the health benefits of reductions in ambient air pollution in South Africa, in: National Association for Clean Air Conference. Mbombela, South Africa.

Balmer, M. 2007. Household coal use in an urban township in South Africa. *J. Energy South. Africa*, 18:27–32.

Barnes, B., Mathee, A., Thomas, E. & Bruce, N. 2009. Household energy, indoor air pollution and child respiratory health in South Africa. *J. Energy South. Africa*, 20:4–13.

Bell, M. L. & Davis, D.L. 2001. Reassessment of the Lethal London Fog of 1952: Novel Indicators of Acute and Chronic Consequences of Acute Exposure to Air Pollution. *Environmental Health Perspectives* 109(3):389-394.

Boldo, E., Linares, C., Aragonés, N., Lumbreras, J., Borge, R., De, D., Pérez-Gómez, B., Fernández-Navarro, P., García-Pérez, J., Pollán, M., Ramis, R., Moreno, T., Karanasiou, A. & López-Abente, G. 2014. Air quality modeling and mortality impact of fi ne particles reduction policies in Spain. *Environ. Res.*, 128:15–26.

Brauer, M., Freedman, G., Frostad, J., Van Donkelaar, A., Martin, R.V, Dentener, F., Van Dingenen, R., Estep, K., Amini, H., Apte, J.S., Balakrishnan, K., Barregard, L., Broday, D.M., Feigin, V., Ghosh, S., Hopke, P.K., Knibbs, L.D., Kokubo, Y., Liu, Y., Ma, S., Morawska, L., Texcalac Sangrador, J.L., Shaddick, G., Anderson, H.R., Vos, T., Forouzanfar, M.H., Burnett, R.T. & Cohen, A. 2016. Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013. *Environ. Sci. Technol.*, 79–88.

Brockington, W.S. 2017. Smog Kills Thousands of Londoners, Salem Press Encyclopedia.

Brook, R.D., Rajagopalan, S., Pope, 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. *Circulation*,121:2331–2378.

Broome, R.A., Fann, N., Navin, T.J., Fulcher, C., Duc, H. & Morgan, G.G. 2015. The health benefits of reducing air pollution in Sydney , Australia. *Environ. Res*., 143:19–25.

Bruce, N., Pope, D., Rehfuess, E., Balakrishnan, K., Adair-Rohani, H. & Dora, C. 2015. WHO indoor air quality guidelines on household fuel combustion: Strategy implications of new evidence on interventions and exposure–risk functions. *Atmos. Environ*.,106:451–457.

Burger, L.W. & Scorgie, Y. 2005. Air Quality Management systems: pitfalls and harmonization. In: Paper presented at the National Association for Clean Air Conference 2005, Cape Town, 30 September.

Burger, R.P &, Piketh, S.J. 2016. Empirical characterization of residential solid fuel burning in South Africa. In: International Global Atmosphere Chemistry Project (IGAC) Science Conference. Breckenridge, CO, USA, 26 - 30 September, p. 3.063.

Cao, J., Yang, C., Li, J., Chen, R., Chen, B., Gu, D. & Kan, H. 2010. Association between long-term exposure to outdoor air pollution and mortality in China: A cohort study. *J. Hazard. Mater*., 186:1594–1600.

Collett, K.S., Piketh, S.J. & Ross, K.E. 2010. An assessment of the atmospheric nitrogen budget on the South African Highveld. *South African journal of science*, 106(5/6):1–9.

Casper, S. 2008. Using EPA's Environmental Benefits Mapping and Analysis Program (BenMAP) for Global Health Impact Analysis.

Chanel, O. 2011. Guidelines on monetary cost calculations related to air-pollution health impacts: Aphekom Project - Deliverable 6.

Daly, A. & Zannetti, P. 2007. An Introduction to Air Pollution – Definitions , Classifications , and History. *Sci. Technol*., 1–14.

DEA. 2009. State of Air Report 2005. A report on the state of the air in South Africa. Pretoria.

DEA. 2012. Highveld Priority Area Air Quality Management Plan Executive Summary.

DEA. 2015. Waterberg-Bonjala Priority Air Quality Management Plan and Threat Assessment.

DEA. 2016. National Environmental Management Act (107 of 1998): Air Quality Offsets Guideline.

DEAT. 2007. Discussion Document: The Establishment of National Standards for Ambient Air Quality. Pretoria: Department of Environmental Affairs and Tourism (DEAT).

DEAT. 2008. Manual for Air Quality Management Planning in South Africa. Pretoria: Department of Environmental Affairs and Tourism (DEAT).

Diab, R.D., Muller, E. & Matooane, M. 2006. Application of Health Risk Assessment Models to South African Conditions. *South African Geogr. J.*, 88:159–165.

Ding, D., Zhu, Y., Jang, C., Lin, C.J., Wang, S., Fu, J., Gao, J., Deng, S., Xie, J. & Qiu, X. 2016. Evaluation of health benefit using BenMAP-CE with an integrated scheme of model and monitor data during Guangzhou Asian Games. *J. Environ. Sci. (China)*, 42:9–18.

DOE. 2013. A survey of energy related behaviour and perceptions in South Africa: the residential sector.

Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G. & Egami, R.T. 2002. The comparison of source contributions from residential coal and low-smoke fuels, using CMB modeling, in South Africa. *Environ. Sci. Policy*, 5:157–167.

Ezzati, M. & Kammen, D.M. 2002. The Health Impacts Of Exposure to Indoor Air Pollution from Solid Fuels in Developing Countries: Knowledge, Gaps, and Data Needs. *Environ. Health Perspect.*,110:1057–1068.

Fann, N., Lamson, A.D., Anenberg, S.C., Wesson, K., Risley, D. & Hubbell, B.J. 2012. Estimating the National Public Health Burden Associated with Exposure to Ambient PM 2 . 5 and Ozone. *Risk Anal.*, 32:81–95.

Feigin, V.L., Roth, G.A., Naghavi, M., Parmar, P., Krishnamurthi, R., Chugh, S., Mensah, G.A., Norrving, B., Shiue, I., Ng, M., Estep, K., Cercy, K., Murray, C.J.L. & Forouzanfar, M.H. 2016. Global burden of stroke and risk factors in 188 countries, during 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. *Lancet Neurol.*, 4422:1–12.

Freiman, M.T. & Tyson, P.D. 2000. The thermodynamic structure of the atmosphere over South Africa: implications for water vapour transport. *Water SA*, 26(2):153–158.

FRIDGE. 2004. Study to examine the potential socio-economic impact of measures to reduce air pollution from combustion. Final Report submitted to the Trade and Industry Chamber: Fund for

Research into Industrial Development Growth and Equity (FRIDGE). Johannesburg: Bentley West Management Consultants.

GBD. 2013. Risk Factors Collaborators, 2015. Global, regional and national comparative risk assessment of 79 behavioural, environmental/occupational and metabolic risks or clusters of risks in 188 countries 1990-2013: a systematic analysis for the Global Burden of Disease Study 2013. *Lancet*, 386:2287–2323.

Hammitt, J.K. & Robinson, L.A. 2011. The Income Elasticity of the Value per Statistical Life: Transferring Estimates between High and Low-income Populations. *J. Benefit-Cost Anal.*, 2.

Harrison, R.M. 2006. Sources of air pollution. (*In* World Health Organization, *ed*. Air quality guidelines: global update 2005. Copenhagen.).

Hubbell, B.J., Fann, N. & Levy, J.I. 2010. Methodological considerations in developing local-scale health impact assessments : balancing national , regional , and local data. *Air Qual. Atmos. Heal*., 99–110.

Huber, M., Knottnerus, J.A., Green, L., Van der Horst, H., Jadad, A.R., Kromhout, D., Leonard, B., Lorig, K., Loureiro, M.I., Van der Meer, J.W.M., Schnabel, P., Smith, R., Van Weel, C. & Smid, H. 2011. How should we define health? *BMJ*, 343.

Hutton, G. 2011. Air Pollution. Global Damage Costs of Air Pollution from 1900 to 2050.

Hutton, G. & Rehfuess, E. 2006. Guidelines for conducting cost-benefit analysis of household energy and health interventions.

Hutton, G., Rehfuess, E. & Tediosi, F. 2007. Evaluation of the costs and benefits of interventions to reduce indoor air pollution. *Energy Sustain. Dev.*, XI.

Kan, H., London, S.J., Chen, G., Zhang, Y., Song, G., Zhao, N., Jiang, L. & Chen, B. 2007. Differentiating the effects of fine and coarse particles on daily mortality in Shanghai, China. *Environ. Int.*, 33:376–384.

Keen, S. & Altieri, K.E. 2016. Assessing the Health Benefits of Attaining and Strengthening Ambient Air Quality Standards in Cape Town, in: National Association for Clean Air Conference. Mbombela, South Africa.

Kelly, F.J. & Fussell, J.C. 2012. Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. *Atmos. Environ.*, 60:504–526.

Kerimray, A., Rojas-Solórzano, L., Torkmahalleh, M.A., Hopke, P.K. & Gallachóir, B.P.Ó. 2017.

Coal use for residential heating: Patterns, health implications and lessons learned. *Energy Sustain. Dev*., 40:19–30.

Khumalo, N. 2016. 2016 State of the air report and national air quality indicator presentation, in: 11th Air Quality Governance Lekgotla. Mbombela, South Africa.

Leiman, A., Standish, B., Boting, A. & Van Zyl, H. 2007. Reducing the healthcare costs of urban air pollution: The South African experience. *J. Environ. Manage*., 84:27–37.

Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., Amann, M., Anderson, H.R., Andrews, K.G., Aryee, M., Atkinson, C., Bacchus, L.J., Bahalim, A.N., Balakrishnan, K., Balmes, J., Barker-Collo, S., Baxter, A., Bell, M.L., Blore, J.D., Blyth, F., Bonner, C., Borges, G., Bourne, R., Boussinesq, M., Brauer, M., Brooks, P., Bruce, N.G., Brunekreef, B., Bryan-Hancock, C., Bucello, C., Buchbinder, R., Bull, F., Burnett, R.T., Byers, T.E., Calabria, B., Carapetis, J., Carnahan, E., Chafe, Z., Charlson, F., Chen, H., Chen, J.S., Cheng, A.T.A., Child, J.C., Cohen, A., Colson, K.E., Cowie, B.C., Darby, S., Darling, S., Davis, A., Degenhardt, L., Dentener, F., Des Jarlais, D.C., Devries, K., Dherani, M., Ding, E.L., Dorsey, E.R., Driscoll, T., Edmond, K., Ali, S.E., Engell, R.E., Erwin, P.J., Fahimi, S., Falder, G., Farzadfar, F., Ferrari, A., Finucane, M.M., Flaxman, S., Fowkes, F.G.R., Freedman, G., Freeman, M.K., Gakidou, E., Ghosh, S., Giovannucci, E., Gmel, G., Graham, K., Grainger, R., Grant, B., Gunnell, D., Gutierrez, H.R., Hall, W., Hoek, H.W., Hogan, A., Hosgood, H.D., Hoy, D., Hu, H., Hubbell, B.J., Hutchings, S.J., Ibeanusi, S.E., Jacklyn, G.L., Jasrasaria, R., Jonas, J.B., Kan, H., Kanis, J. a., Kassebaum, N., Kawakami, N., Khang, Y.H., Khatibzadeh, S., Khoo, J.P., Kok, C., Laden, F., Lalloo, R., Lan, Q., Lathlean, T., Leasher, J.L., Leigh, J., Li, Y., Lin, J.K., Lipshultz, S.E., London, S., Lozano, R., Lu, Y., Mak, J., Malekzadeh, R., Mallinger, L., Marcenes, W., March, L., Marks, R., Martin, R., McGale, P., McGrath, J., Mehta, S., Mensah, G. a., Merriman, T.R., Micha, R., Michaud, C., Mishra, V., Hanafiah, K.M., Mokdad, A. a., Morawska, L., Mozaffarian, D., Murphy, T., Naghavi, M., Neal, B., Nelson, P.K., Nolla, J.M., Norman, R., Olives, C., Omer, S.B., Orchard, J., Osborne, R., Ostro, B., Page, A., Pandey, K.D., Parry, C.D.H., Passmore, E., Patra, J., Pearce, N., Pelizzari, P.M., Petzold, M., Phillips, M.R., Pope, D., Pope, C.A., Powles, J., Rao, M., Razavi, H., Rehfuess, E. a., Rehm, J.T., Ritz, B., Rivara, F.P., Roberts, T., Robinson, C., Rodriguez-Portales, J. a., Romieu, I., Room, R., Rosenfeld, L.C., Roy, A., Rushton, L., Salomon, J. a., Sampson, U., Sanchez-Riera, L., Sanman, E., Sapkota, A., Seedat, S., Shi, P., Shield, K., Shivakoti, R., Singh, G.M., Sleet, D. a., Smith, E., Smith, K.R., Stapelberg, N.J.C., Steenland, K., Stöckl, H., Stovner, L.J., Straif, K., Straney, L., Thurston, G.D., Tran, J.H., Van Dingenen, R., Van Donkelaar, A., Veerman, J.L., Vijayakumar, L., Weintraub, R., Weissman, M.M., White, R. a., Whiteford, H., Wiersma, S.T., Wilkinson, J.D., Williams, H.C., Williams, W., Wilson, N., Woolf, A.D., Yip, P., Zielinski, J.M., Lopez, A.D., Murray, C.J.L. & Ezzati, M. 2012. A comparative risk assessment of

burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: A systematic analysis for the Global Burden of Disease Study 2010. Lancet, 380: 2224–2260.

MacLean, S.J. 2005. Human Security as Freedom from Want: Inequities and Health in South Africa. *Policy Soc.*, 24:48–72.

Mathee, A. & Wright, C. 2014. Environmental health in South Africa. *South African Heal. Rev.*, 2013/2014:105–116.

Matooane, M. & Diab, R. 2011. Why we need to manage air quality. *Publ. Ser.*, A B.:4.

Mehta, S. & Shahpar, C. 2004. The health benefits of interventions to reduce indoor air pollution from solid fuel use : a cost-effectiveness analysis. *Energy Sustain.*,Dev. 3:53–59.

Mekwa, N.J., Madela-Mntla, E.N., Loots, G., Van Niekerk, A., Jeenah, M. & Mayosi, B.M. 2016. The development of a National Health Research Observatory in South Africa:considerations and challenges. In: Padarath, A., King, J.E.M., Casciola, J. (Eds.), *South African Health Review*, 2016:235-241.

Miller, T.R. 2000. Variations between countries in values of statistical life. *J. Transp. Econ. Policy*, 34:169–188.

Naidoo, S., Piketh, S.J. & Curtis, C. 2014. Quantification of Emissions Generated from Domestic Burning Activities from Townships in Johannesburg. Data and Methodology, 24:34–41.

Naiker, Y., Diab, R.D., Zunckel, M. & Hayes, E.T. 2012. Introduction of local Air Quality Management in South Africa : overview and challenges. *Environ. Sci. Policy*, 17:62–71.

Norman, R., Cairncross, E., Witi, J. & Bradshaw, D. 2007. Estimating the burden of disease attributable to urban outdoor air pollution in South Africa in 200. *SAMJ*, 97:782–790.

OECD. 2003. OECD Glossary of Statistical Terms - Indoor air pollution Definition. https://stats.oecd.org/glossary/detail.asp?ID=1336 Date of access: 9 Aug. 2017.

OECD. 2016a. The Economic Consequences of Outdoor Air Pollution. Paris.

OECD. 2016b. The Economic Consequences of Outdoor Air Pollution.

OECD. 2011. Valuing Mortality Risk Reductions in Regulatory Analysis of Environmental , Health and Transport Policies: Policy Implications.

Ojelede, M.E., Annegarn, H.J., Price, C., Kneen, M.A. & Goyns, P. 2008. Lightning-produced NOx budget over the Highveld region of South Africa. *Atmospheric environment*, 42(22):5706–5714.

Ostro, B. 2006. Health impact assessment (*In* WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulphur dioxide). Geneva: World Health Organization.

Pascal, M., Corso, M., Chanel, O., Declercq, C., Badaloni, C., Cesaroni, G., Henschel, S., Meister, K., Haluza, D., Martin-Olmedo, P. & Medina, S. 2013. Assessing the public health impacts of urban air pollution in 25 European cities: Results of the Aphekom project. *Sci. Total Environ*., 449: 390–400.

Pascal, M., Corso, M., Ung, A., Declerq, C. & Medina, S. 2011. Improving Knowledge and Communication for Decision Making on Air Pollution and Health in Europe (Aphekom): Guidelines for assessing the health impacts of air pollution in European cities.

Peters, A. & Pope, C.A. 2002. Cardiopulmonary mortality and air pollution. *Lancet*, 360:1184–1185.

Pope, C.A. & Dockery, D.W. 2006. Critical Review: Health Effects of Fine Particulate Air Pollution : Lines that Connect. *Air & Waste Manag. Assoc*., 709–742.

Pope, C.A., Turner, M.C., Burnett, R.T., Jerrett, M., Gapstur, S.M., Diver, W.R., Krewski, D. & Brook, R.D. 2015. Relationships between fine particulate air pollution, cardiometabolic disorders, and cardiovascular mortality. *Circ. Res*., 116.

Quigley, R., Den Broeder, L., Furu, P., Bond, A., Cave, B. & Bos, R. 2006. Health Impact Assessment International Best Practice Principles. Special Publication Series No. 5.

Raghunandan, A., Matooane, M. & Oosthuizen, R. 2008. Impacts of Air Pollution. Publication series B: Book 5.

Reiss, R., Anderson, E.L., Cross, C.E., Hidy, G., Hoel, D., McClellan, R. & Moolgavkar, S. 2007. Evidence of health impacts of sulfate-and nitrate-containing particles in ambient air. *Inhal. Toxicol*., 19:419–449.

Rollin, H. 2017. Editorial Evidence for health effects of early life exposure to indoor air pollutants: what we know and what can be done. *Clean Air J*., 27:2–3.

Samet, J.M., Brauer, M. & Schlesinger, R. 2006. Particulate matter (in WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulphur dioxide. Global update 2005:217-305*)*. Geneva: World Health Organization.

Scorgie, Y., Kneen, M.A., Annegarn, H.J. & Burger, L.W. 2003. Air pollution in the Vaal Triangle - Quantifying source contributions aand identifying cost-effective solutions. *Clean Air J.*, 13:5–18.

Scott, V., Schaay, N., Schneider, H. & Sanders, D. 2017. Addressing, South African Health Review 2017.

Smith, K.R., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z., Dherani, M., Hosgood, H.D., Mehta, S., Pope, D. & Rehfuess, E. 2014. Millions Dead: How Do We Know and What Does It Mean? Methods Used in the Comparative Risk Assessment of Household Air Pollution. *Annu. Rev. Public Health*, 35:185–206.

Solar, O. & Irwin, A. 2010. A conceptual framework for action on the social determinants of health. Social Determinants of Health Discussion Paper 2.

South Africa. 2004. National Environmental Management: Air Quality Act No. 39 of 2004. Pretoria.

South Africa. 2006. Declaration of the Vaal Triangle air-shed priority area in terms of Section 18(1) of the National Environmental Management: Air Quality Act (No. 39 of 2004). (Government notice no. 365). *Government Gazette,* 28732. 21 Apr.

South Africa. 2007. Declaration of the Highveld as priority area in terms of Section 18(1) of the National Environmental Management: Air Quality Act (No. 39 of 2004). (Government notice no. 1123). *Government Gazette,* 30518. 24 Nov.

South Africa. 2008. Notice of intention to establish the Vaal Triangle Air-Shed Priority Area air quality management plan in terms of Section 18(1) of the National Environmental Management: Air Quality Act (No. 39 of 2004). (Government notice no. 1141). *Government Gazette,* 31615. 21 Nov.

South Africa. 2009. National Ambient Air Quality Standards. *Government Gazette*, No.32816 (Notice 1210), pp. 6–9.

South Africa. 2016. National Environmental Management Act (no. 107 of 1998): Air quality offsets guideline. (Government Notice no. 33). *Government Gazette,* 39833. 18 Mar.

Stanek, L.W., Sacks, J.D., Dutton, S.J. & Dubois, J.J.B. 2011. Attributing health effects to

apportioned components and sources of particulate matter: An evaluation of collective results. *Atmos. Environ.*, 45:5655–5663.

StatsSA. 2014. General Household Survey 2013. Statistical release P0318. Pretoria.

Terblanche, A.P., Nel, C.M. & Tosen, G.R. 1995. Respiratory health impacts of three electrification scenarios in South Africa. *J. Energy South. Africa*, 93–96.

U.S. EPA. 2016. Valuing mortality risk reductions for policy: a meta-analytic approach. Washington, D.C.

U.S. EPA. 2012. Provisional Assessment of Recent Studies on Health Effects of Particulate Matter Exposure. Research Triangle Park,NC.

U.S. EPA. 2011. The Benefits and Costs of the Clean Air Act from 1990 to 2020: Summary Report.

ANNEXURES

North-West University

11 Hoffman Street

Potchefstroom

2531

17 November 2017

To whom it may concern:

Dear Sir or Madam:

We, the undersigned and co-authors of the manuscripts listed below, herewith give permission that these manuscripts can be submitted for degree purposes by Louisa Farina Lindeque.

Lindeque, L.F., Burger, R.P. & Piketh, S.J. 2016. Health impact assessment of interventions to reduce solid fuel burning: challenges and considerations. In: *National Association for Clean Air.* ISBN: 978-0-620-70646-9, Mbombela, South Africa, 10-13 October 2016.

Lindeque, L.F., Burger, R.P. & Piketh, S.J. 2016. The health and economic benefits of thermal insulation interventions to improve air quality in a South African township. *Aerosol and Air Quality Research.*

Lindeque, L.F., Burger, R.P., & Piketh, S.J., 2017. The health and economic benefits of thermal insulation as air quality intervention on the Highveld. Unpublished work

Whilst we were involved in the conceptualisation of this work, Farina Lindeque was primarily responsible for the execution and documentation of this research.

Sincerely,

Dr Roelof P. Burger

Roelof.Burger@nwu.ac.za

Prof Stuart J. Piketh

Stuart.Piketh@nwu.ac.za