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Contents

Editorial

2 Clean Air Journal's 45th anniversary
CAJ archive highlights the importance of continuous air quality measurements

Highlighted local research

4 Summary of research paper published in Journal of Energy in Southern Africa titled: A perspective of South African coal-fired power station emissions
(2015) Volume 26 Issue 3 pages 27-40

5 Summary of research paper submitted to Atmospheric Chemistry and Physics titled: Optical and microphysical characterization of aerosol layers over South Africa by means of multi-wavelength polarization Raman lidar measurements

News

6 Obituary: Clive Turner

7 National Association for Clean Air (NACA) Awards

Research articles

9 **Corrections and amendments**
Retraction: New particle formation events in semi-clean South African Savannah

10 Correcting respirable photometric particulate measurements using a gravimetric sampling method

15 Influence of coal-particle size on emissions using the top-lit updraft ignition method

21 Assessment of ambient air pollution in the Waterberg Priority Area 2012-2015

Editorial
Clean Air Journal's 45th anniversary
CAJ archive highlights the importance of continuous air quality measurements

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The Clean Air Journal celebrates its 45th year in 2016. The first issue started with an article on the problems with the application of the Atmospheric Pollution Prevention Act in South Africa (Boegman, 1971), and also included an article on Johannesburg's "good fortune" at having 3 000 acres of mine dumps available to revegetate into City Parks (Cook, 1971). Since 1971, the Clean Air Journal has aimed to report authentic scientific articles on the topic of air quality management and monitoring relevant to southern Africa.

Since starting the Clean Air Journal twitter handle (@CleanAirJ) earlier this year, I have been enjoying tweeting links to articles from the Clean Air Journal archives for Throwback Thursdays (#tbt). Writing these tweets has afforded me the opportunity to read through the Table of Contents from the Clean Air Journal's archives, and read countless articles. The history of air quality management, monitoring and atmospheric science contained in these archives is well-documented and thought-provoking.

While reading through these articles, it is striking how critical continuous and regular measurements are in improving our understanding of our atmosphere and of air quality. There are outstanding examples of regular monitoring in South Africa. Three such networks that I have found in my reading is a national network of sampling smoke and SO_2 started by the Council for Scientific and Industrial Research (CSIR) in 1955 (e.g. Kemeny, 1980; Kemeny and Wells, 1982), the Global Atmospheric Watch (GAW) at Cape Point (e.g. Brunke, 1983; Labushagne et al., 2002; Brunke et al, 2010), and the Deposition of Biogeochemically Important Trace Species-International Global Atmospheric Chemistry (IGAC) DEBITS in Africa (DEBITS-IDAF) network (e.g. Maritz, 2015). The strength in these networks is the high-quality, consistent and continuous monitoring. This has been achieved through well-developed and consistently applied methodologies for monitoring, data capture and reporting. In addition, through the long datasets reported in these papers, and with the knowledge of how difficult it is to keep instruments running (especially in far-off monitoring stations!), the attention to maintenance and upkeep of the networks is evident.

These networks are not the only successful long-term monitoring networks in South Africa; but, they do provide great examples of the hard work and dedicated resources needed to develop and maintain such high quality networks and databases. They also highlight the insights only regular and extended monitoring can provide. Two figures from Kemeny and Wells (1982) are shown below, which highlight the levels and trends in smoke pollution from 1950's-1980's (Figure 1) and concentrations of Mn and Pb in aerosol particles in Port Elizabeth (Figure 2). Without regular monitoring over the years, trends could not have been calculated and/or observed, and there would be no efficient way of verifying the success of regulatory policies. The results

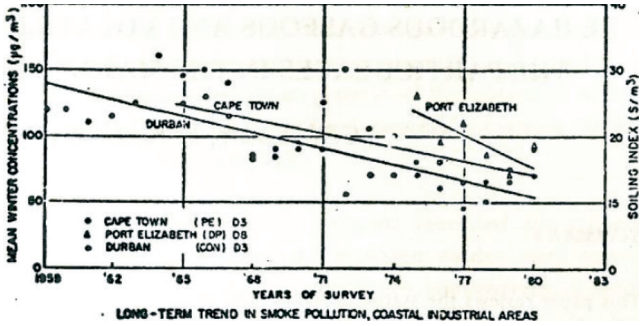

***Figure 1**: Mean winter concentration of smoke in coastal industrial areas in South Africa (taken from Kemeny and Wells, 1982).*

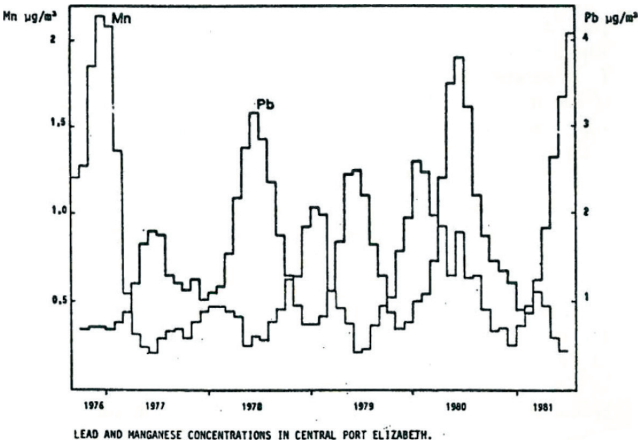

***Figure 2**: Lead (Pb) and manganese (Mn) concentrations in Port Elizabeth (taken from Kemeny and Wells, 1982).*

from this research provide a strong understanding of air quality in South Africa, and also provide a baseline for quantifying air quality trends over the past decades.

Let's look back at the 45-year history of the Clean Air Journal and reflect on the great research performed by the community and documented in the archives. It is important to remember the critical need to develop and to sustain continuous and

regular air quality monitoring. On-going research networks, such as DEBITS and GAW, continue to provide datasets that are invaluable, in large part, due to their continuity and high-quality measurements. Both of these on-going networks have had national and international impact. From the Cape Point GAW station that is the oldest continuous record of CO measurements in the Southern Hemisphere, to DEBITS that measure, among other things, the trends in acidic compounds in South Africa. In addition, the government-owned compliance monitoring networks can contribute greatly, as they provide invaluable insights into the state of air quality and, as they continue to operate continuously, into the trends in air quality across the country.

The monitoring networks that we begin now, and foster and grow, are the datasets the next generation of scientists will use to understand the impact of air quality management policies, as well as the impacts of climate change on air quality in Africa. To nurture such networks needs a collaborative effort of the whole community of scientists and policy makers.

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Highlighted local research

Summary of research paper published in Journal of Energy in Southern Africa titled:

A perspective of South African coal-fired power station emissions

(2015) Volume 26 Issue 3 pages 27-40

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Emissions from South African coal-fired power plants are significant on a regional and global scale. Globally, South Africa ranks seventh of the top 10 countries that are responsible for more than 85% of global carbon emissions from coal-fired plants (preceded only by China, USA, India, Germany, Russia and Japan and superseded by Australia, Korea and Poland). The carbon dioxide (CO_2) emissions intensity (CO_2 emissions per economic output) of South Africa was found to be one of the highest in the world and more than triple that of industrialized countries. Regionally, South Africa is the main power generator in Africa and the energy sector (of which around 83% is contributed by coal-fired power plants) is one of the major emitters of criteria (Particulate Matter (PM), Nitrogen Dioxide (NO_2), and Sulphur Dioxide (SO_2)) pollutants in the country.

The reasons for the high emissions from South African coal fired power stations are the high reliance on coal as a fuel (coal is a fuel that is more difficult to burn cleanly than other fossil fuels) and the high specific emissions associated with South African coal combustion.

Even though the South African government is trying to reduce the country's dependence on coal; it will remain a dominant source of energy in South Africa, at least in the medium term. The country's coal use for electricity supply is expected to rise as two new power stations, namely Medupi and Kusile are added to the fleet and another 2450 MW of new build coal-fired power plants are planned between 2010 and 2030 (IRP, 2013).

Because South African coal-fired power station emissions are so prominent globally and regionally, it is important to understand the effects of changes (especially those changes that can lead to increases) on emissions. The paper entitled "A perspective on South African coal fired power station emissions", recently published in the Journal of Energy in Southern Africa (Pretorius et al., 2015) investigates the effect the South African energy crisis had (and has) on emissions from coal-fired power stations and makes projections of future emissions based on different future scenarios.

The first signs of the energy crisis were evident in the early 2000s when the electricity reserve fell well below the aspired 15%. During the end of 2007and beginning of 2008 the energy system could not keep up with demand (at an electricity reserve of around 6%) and load shedding was implemented for the first time.

In 2008, a decision was made to defer maintenance at major coal-fired power stations amidst the increasing pressure the South African government placed on Eskom to 'keep the lights on' at all cost. This lead to the decline in performance of the fleet and three older power stations that were mothballed during the 1980s and early 1990s returned back to service to alleviate the pressure on existing stations. The overall effect was a decrease in the thermal efficiency of the coal-fired power station fleet of around 8% between 2005 and 2012. During this period, coal quality remained relatively stable with an average calorific value of 19.25 (MJ/kg) and a standard deviation of 0.34 (with the exception of sulphur content of coal which declined by around 8% at times from 2005 to 2012). The deteriorating thermal efficiency meant that approximately 8% more coal had to be burned in 2011 compared to 2005 in order to produce the same amount of energy. This led to an increase of all criteria pollutants (with the exception of SO_2 – as the sulphur content of fuel coals decreased) and CO_2. Apart from the increase in emissions due to a decrease in thermal efficiency, PM emissions further increased due to increased pressure on PM abatement and lowered maintenance opportunity. The lesson learned from the increase of emissions during the energy crisis is of global importance as many countries in the world are currently facing energy shortages, including major developing countries such as China and India.

The paper continues to make projections of future coal-fired power station criteria and CO_2 emissions. Four future (2015 to 2030) scenarios are explored. Three of the four scenarios are based on the lower projected energy demand baseline case as published in the updated Integrated Development Plan (IRP). The difference between these three scenarios is different retrofit rates of power stations with emissions abatement technologies. The fourth scenario is a worst case scenario and assumes high energy demand (and therefore no decommissioning of power stations), high emission rates (similar to worst past emission rates during the period 1999-2012) and no further abatement of emissions above and beyond current mitigation efforts. This scenario gives an indication of what South African coal-fired power station emissions could look like if the energy crisis persists.

The research found that there are marked differences between the various scenarios for all pollutants. Worst case PM emissions was projected to rise by 40% compared to a 2015 baseline value whereas best case PM emissions were projected to decline by 40% against the same value. Worst case NO_x emissions were predicted to increase by 40% in 2030 from a 2015 baseline value and best case emissions are expected to decline 10% from the same level in 2030. Worst case SO_2 emissions were predicted to increase by around 38% in 2030 when best case emissions were expected to decrease by around 20% in 2030 from a 2015 baseline value. CO_2 emissions projections indicate that it is very unlikely that the South African climate commitment target for 2030 will be met. The difference in projections highlights the importance of the various assumptions made in each scenario and most importantly show how emissions will increase if energy demand remains high and the energy crisis persists.

Highlighted local research

Summary of research paper submitted* to Atmospheric Chemistry and Physics titled:

Optical and microphysical characterization of aerosol layers over South Africa by means of multi-wavelength polarization Raman lidar measurements

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*Editor's Note: The paper is still in the ACP Discussion stage but has been accepted with minor revisions

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Optical and microphysical properties of different aerosol types over South Africa were measured with a multi-wavelength polarization Raman lidar at Elandsfontein in the Highveld region of South Africa for one year. The observations were performed within the framework of the EUCAARI (European Integrated project on Aerosol, Cloud, Climate, and Air Quality Interactions) campaign of which the aim was to characterize particles in terms of physical, optical and chemical aerosol properties in order to reduce the uncertainty associated with aerosol with 50%. Since limited long-term data of this nature exists for this region, this study could significantly assist in bridging existing gaps relating to aerosol properties over South Africa.

A multi-wavelength PollyXT Raman lidar system was used to determine vertical profiles of aerosol optical properties, i.e. extinction and backscatter coefficients, Ångström exponents, lidar ratio and depolarization ratio. In addition, the mean microphysical aerosol properties, i.e. effective radius and single scattering albedo were retrieved with an advanced inversion algorithm. Thirty eight urban/industrial, biomass burning, and mixed biomass burning and desert dust aerosols atmospheric aerosol layers were studied. Raman lidar observations were combined with backward trajectory analysis, satellite fire observations and in situ data to identify sources of the elevated aerosol layers.

The results indicated clear differences between the intensive optical properties of biomass burning and urban/industrial aerosols in atmospheric layers. The measurements revealed a wide range of optical and microphysical parameters for biomass burning aerosols. The results indicates probable mixing of biomass burning aerosols in the area with desert dust particles, as well as the possible continuous influence of urban/industrial aerosol load in the region. The Lidar ratio at 355 nm, the linear particle depolarization ratio at 355 nm and the extinction-related Ångström exponent from 355 to 532 nm were 52 ± 7 sr; 0.9 ± 0.4 % and 2.3 ± 0.5, respectively for urban/industrial aerosols, while these values were 92 ± 10 sr; 3.2 ± 1.3 %; 2.0 ± 0.4, respectively for biomass burning aerosols layers. The study also indicated that biomass burning particles are larger and slightly less absorbing compared to urban/industrial aerosols. The particle effective radiuses were found to be 0.10 ± 0.03 µm, 0.17 ± 0.04 µm and 0.13 ± 0.03 µm for urban/industrial, biomass burning, and mixed biomass burning and desert dust aerosols, respectively, while the single scattering albedo at 532 nm were 0.87 ± 0.06, 0.90 ± 0.06, and 0.88 ± 0.07 (at 532 nm), respectively for these tree types of aerosols. The results for the analysed aerosol types in this study agreed very well with similar studies reported in literature.

News
Obituary: Clive Turner

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It is with great sadness that the National Association for Clean Air and the editorial board of the Clean Air Journal would like to acknowledge the recent death of Clive Turner. We would like to commemorate the immeasurable contribution that he made to the cause of clean air in South Africa. Clive was one of the founders of the discipline of Air Quality in South Africa, and was instrumental in many of the initial studies relating to air quality management and atmospheric chemistry and transport. The findings from that work still influence how we perceive the core issues and concerns of air quality in the country.

Clive Turner graduated in England as a Physicist in 1973 and started work in the power industry, initially with a leading turbine manufacturer. In 1976 he joined ESKOM in Johannesburg, initially working in the area of mathematical modelling of machine vibration and structural dynamics, he later moved on to become an acknowledged air quality specialist and, in the late 1970s, was to found what became Eskom's multi-disciplinary environmental research facility. Before retiring from Eskom in 2011, he was to become Eskom's Corporate Environmental Consultant (air and rain) in the Sustainability and Innovation Department. He was an acknowledged expert in the environmental impacts of power plants, global climate change, air quality monitoring, acid deposition, dispersion modelling, atmospheric chemistry, environmental research management, and environmental law and the consequent negotiation and enforcement processes.

During the late 1970s – mid 2000s Clive was involved in the installation of the operation of a network of fifteen air quality monitoring stations over the Highveld. He maintained high levels of data quality from this network and for many years this was the benchmark air quality monitoring network in South Africa and set the basis for our knowledge of air quality over the industrialised Highveld regions of South Africa.

Due to the international interest, during the 1980s in the impacts of acid deposition resulting from fossil fuel combustion; Clive, through his team at Eskom, collaborated in studies on sulphur dioxide deposition and acid rain formation. This strongly impacted our understanding of the impacts of wet and dry deposition from the industrial plumes over the South African Highveld. Clive is credited with driving advances in describing unique dispersion phenomena from tall stacks, associated with convective cells over the Mpumalanga Highveld that resulted in high SO_2 concentrations being observed within a few kilometres of the base of the stacks. This research helped improve how dispersion models accounted for vertical transport of pollutants in highly convective environments. With colleague Gerhard Held, he made important contributions in describing and quantifying the regional scale dispersion and recirculation of SO_2 plumes over southern Africa and adjacent oceans.

Clive supported and sustained a vigorous programme of research collaboration with academic scientists. He mediated with Eskom to continue supporting long term research goals, as well as research into the immediate issues facing Eskom. This led to ongoing Eskom support for the SAFARI'92, the SAFARI 2000 and the DEBITS passive monitoring campaigns. Clive actively supported several initiatives for airborne sampling on a variety of aircraft, leading eventually to South Africa having world-class indigenous capacity in the field of airborne sampling.

In 2001, Clive was seconded to the Department Of Environmental Affairs to assist with the national climate change programme and environmental law reform, where he was employed for three years. Whilst in government, he was the lead author for the South African National Climate Change Response Strategy, published in 2004.

Between 2004 and 2007, Clive served as a lead author for the energy chapter of the Mitigation Volume of the Intergovernmental Panel on Climate Change Fourth Assessment Report. This report was to culminate in the IPCC being awarded the Nobel Peace Prize in 2007.

Clive was an excellent leader and project coordinator; always ready to share his vast knowledge and experience with colleagues and especially young, upcoming scientists and technicians, which resulted in the establishment of several "Centres of Excellence" at different Universities in SA, subsequently producing some of today's leading researchers in the field of air quality. His ultimate guiding principles were always towards good science and cooperative science. The ethos that he nurtured, specifically within Eskom, endures to this day, of treating corporate, academic, regulatory and civil society scientists as partners in a joint endeavour towards clean air.

Dr Gregor Feig
President: National Association for Clean Air

News
National Association for Clean Air (NACA) Awards

http://dx.doi.org/10.17159/2410-972X/2016/v26n1a5

Every year, NACA presents awards to recognise the contribution of individuals and industries to improving the Air Quality in South Africa. During the 2015 NACA conference awards the NACA leadership award, the NACA Golden Award and the NACA Mining and Industry award were presented.

NACA Leadership in Air Quality Award: Mr Peter Lukey

The NACA Leadership in Air Quality Award is made annually to recognise exceptional efforts in one of the following fields:

- Research leading to understanding of the mechanism of air pollution in the broadest sense (Chemistry, Atmospheric Sciences)
- Research and/or development leading to improved methods or processes for the characterisation or reduction of air pollution
- The promotion of education/training in atmospheric pollution
- Service in a non-governmental organisation in an atmospheric pollution-related field. Enhancement of public awareness, management of air pollution at local or regional scale, or exceptional leadership to minimise the impact on the environment must be demonstrated
- Public service employees, for innovative, dedicated and/or long-term efforts in the reduction of atmospheric pollution
- A consistent effort at regional or local scale in the provision of high-quality monitoring results

Upon consideration of the conceptual and practical leadership that Mr Peter Lukey manifested in shaping the debate and influencing national policy on air quality and climate protection, and the immense contributions that he has made to the field of air quality management in South Africa over the past twenty years, the National Association for Clean Air (NACA) honoured his achievements by presenting him with the 2015 NACA Leadership in Air Quality Award.

Peter Lukey is a Civil Engineering Technologist who, after nine years as a contractor, left the construction industry to pursue his environmental interests. At Wits University, Peter completed his BSc Degree majoring in botany and advanced biological science (ecology), as well as co-founding the environmental activist organisation Earthlife Africa. He served as Earthlife's National Coordinator in the early days of the organization's development.

Following a period of 'committed activism', Peter took up a position as Environmental Programme Coordinator for the Danish development assistance agency DanCED (The Danish Cooperation for Environment and Development). At the end of 2000, Peter left DanCED, after five years of working on environmental project support in the region, and took up the position of Project Manager for the Department of Environmental Affairs and Tourism's Environmental Protection Support Unit (EPSU). On the 1st of August 2003, Peter became the department's Chief Director: Regulatory Services where he was involved in setting up the so-called "Green Scorpions". On 1 July 2005, Peter became the department's Chief Director: Air Quality Management and Climate Change with the challenge of implementing the new Air Quality Act, a role he held until 2012. During this period Peter was influential in developing the National Framework for Air Quality Management which has guided the implementation of the Act. It was under his leadership that the South African Air Quality Information System was developed and the priority area ambient air quality monitoring networks were established.

Peter is currently the Chief Policy Advisor: Strategic Environmental Intelligence in the Environmental Advisory Services of the DEA, as such he still has an intimate involvement with the Air Quality community.

Golden Award: Dr Hanlie Liebenberg-Enslin

The NACA 'Golden Award' is intended to acknowledge an individual who has made an exceptional contribution to the air quality field in South Africa, either through specific studies or projects they have been involved in, or through involvement in the clean air community.

The 2015 award was made to Dr Hanlie Liebenberg-Enslin, in recognition of the exceptional contribution that she has made over many years to both improving the understanding and management of air quality in South Africa and through her involvement in the South African clean air community.

Hanlie is a former president of NACA and IUAPPA. During her tenure of both organisations she forged a closer working relationship between the South African and international Air Quality communities and she was instrumental in bringing the international IUAPPA conference to Cape Town in 2013.

Hanlie is Managing Director and joint founder of Airshed Planning Professionals. She is a skilled dispersion modeller, has worked on projects throughout southern Africa, and regularly teaches courses on air quality management. Hanlie received her PhD, focusing on Aeolian dust transport, in 2014.

We thank Hanlie for everything she has done to promote both NACA and the cause of clean air in South Africa.

NACA Mining and Industry Award: ArcelorMittal Vanderbijlpark Works

ArcelorMittal Vanderbijlpark Works representative, Johan Hattingh, receiving the NACA Mining and Industry Award

The NACA Mining and Industry award is made on an annual basis to recognise the concrete efforts and contributions made by industry to improve their air quality impact.

The 2015 NACA Mining and Industry award was made to ArcelorMittal Vanderbijlpark Works. Since 2005, the ArcelorMittal Vanderbijlpark Works have consistently implemented improvements in their air quality emission abatement actions, including the following:

- Production changes to reduce potassium chloride emissions;
- Improvements in maintenance and operations to reduce occurrence of upset conditions,
- Decommissioning of two coke batteries
- Rehabilitation of waste disposal sites and contaminated land to reduce wind erosion emissions,
- Installation of two new bag houses,
- Installation of water bausers for waste piles,
- Improvement of the material handling processes and enclosing tip stations, and
- Remediation of historic storage areas.

The results of these remediation efforts are that the dust emissions from the ArcelorMittal Vanderbijlpark Works have dropped from 6 120 tons in 2005 to 1 187 tons in 2014. This is a total reduction of 81%. The dust emissions from ArcelorMittal Vanderbijlpark Works point emissions are now 76% lower than the national minimum emission standards. We commend ArcelorMittal for the efforts made in reducing their impact on air quality in the Vaal Triangle region.

Corrections and amendments
Retraction: New particle formation events in semi-clean South African Savannah

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Ville Vakkari, Heikki Laakso, Markku Kulmala, Ari Laaksonen, Desmond Mabaso, Moses Molefe, Nnenesi Kgabi, John P Beukes, and Lauri Laakso. 2011. New particle formation events in semi-clean South African Savannah, *Clean Air Journal*, 20 (2).

This article has been retracted by the Editors and the Authors due to redundant publication (Vakkari et al., 2011). This article was originally submitted to the National Association of Clean Air (NACA) 2011 conference as a conference paper. It was mistakenly included in the Clean Air Journal as a peer-reviewed original article.

Reference

Vakkari et al. 2011. New particle formation events in a semi-clean South African savannah. *Atmospheric Chemistry and Physics*, 11, 3333-3346.

Correcting respirable photometric particulate measurements using a gravimetric sampling method

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Abstract
According to the National Environmental Management: Air Quality Act of 2004 people have the right to clean air and a healthy environment. Particulate matter (PM) emissions pose a significant health threat. Both indoor and ambient air pollution contribute to the burden of disease associated with poor air quality. This is particularly true within the South African setting where low income households make use of different solid fuels for heating and cooking purposes resulting in high levels of PM emissions. This paper focuses on the evaluation mass concentration measurements recorded by continuous photometric PM instruments within KwaDela, a low income settlement in Mpumalanga located on the South African Highveld. Thus, obtaining a photometric calibration factor for both the DustTrak Model 8530 and the SidePak AM510. Sampling took place during August 2014 for a period of seven days. The photometric and gravimetric instruments were collocated within the indoor environment of selected households. These instruments were all fitted with 10mm Dorr-Oliver Cyclone inlets to obtain the respirable (PM_4) cut-point. The study found that both instruments tend to overestimate the indoor particulate mass concentrations when compared to the reference gravimetric method. The estimated photometric calibration factors for the DustTrak Model 8530 and SidePak AM510 are 0.14 (95%Cl: 0.09, 0.15) and 0.24 (95%Cl: 0.16, 0.30) respectively. The overestimation of the photometric measurements is rather significant. It is therefore important that the correction factors are applied to data collected in indoor environments prone to the combustion of solid fuels. The correction factors obtained from this and other studies vary as a result of the environment (ambient, indoor etc.) as well as the aerosol size fraction and the origin thereof. Thus, it is important to considered site specific calibration factors when implementing these photometric light-scattering instruments.

Keywords
respirable particulate matter, gravimetric analysis, light scattering photometer, photometric calibration factor; indoor air quality

Introduction
According to the World Health Organisation (2006) having access to air of good quality is necessary for a healthy life, this statement is supported by the South African National environmental management: Air Quality Act 39 of 2004. However, air pollution continues to be a major health problem globally, causing an estimated seven million premature deaths a year. The majority of these deaths are associated with the populations of developing countries (WHO, 2014).

The 2010 Global burden of disease study indicated that an estimated 3.5 million (uncertainty level: 2.7, 4.5) premature deaths are caused by household solid fuel use, an additional 0.5 million deaths can be attributed to ambient air pollution resulting from household emissions (Bruce et al., 2015). It is thus no surprise that the study rated ambient air pollution as the ninth and indoor air pollution as the third leading risk factors associated with the global burden of disease (Lim et al., 2012).

Recently focus has been drawn to the significance of indoor exposure to PM as most people tend to spend more than 85% of their time indoors (Yassin et al., 2012; Funk et al., 2014). Most data collected on PM concentrations are based on ambient measurements, which is not a reliable indicator of the particulate levels associated with indoor and personal exposures (Huang et al., 2007).

Measuring of particulate mass concentrations, which is the most widely reported parameter, is conducted mainly for scientific and regulatory reasons (McMurry, 2000).

The WHO and South African National Ambient Air Quality Standards (NAAQS) have set guidelines for exposure to PM_{10} and $PM_{2.5}$. The exposure guidelines for the annual and 24-hour averaging period for both PM_{10} and $PM_{2.5}$ are represented in Table 1. There is a significant difference between the WHO and NAAQS as the guidelines set by the WHO are much lower than those set by the NAAQS. It is important to note that there are no set guidelines for indoor PM exposure as the South African guidelines focus on ambient exposure. There is, however, not a set guideline for the respirable particulate fraction (PM_4) investigated in this study.

***Table 1**: WHO and NAAQS*

		24 Hour (µg/m³)	1 Year (µg/m³)
PM_{10}	**WHO**	50	20
	NAAQS	75	40
$PM_{2.5}$	**WHO**	25	10
	NAAQS	65	25

Source: South Africa (2009 & 2012) and WHO (2006).

Ground-based PM monitoring is usually performed by using either continuous measurements collected by real-time PM monitoring instruments or filter-based manual sampling methods (Engel-Cox et al., 2013). The filter-based sampling method is a time integrated method obtaining PM mass concentrations through direct measurements, whereas the continuous instruments are based on various technologies and considered as an indirect measurement method. Continuous monitoring measurements make it possible to gain insight into levels of PM during shorter time intervals (Tasić et al., 2012).

Light-scattering photometers, such as the DustTrak Model II 8530 and SidePak AM510 (TSI Inc., Shoreview, MN, USA), are commonly used to measure PM mass concentrations (TSI Inc., 2002; Kim et al., 2004; TSI Inc., 2014). Previous studies done relating to the DustTrak (Tung et al., 1999; ; Heal, et al, 2000; Ramachandran, et al, 2000; Chung, et al, 2001; Yanosky et al., 2002; Braniš and Hovorka, 2005; Kingham, et a., 2006; McNamara et al., 2011; Wallace, et al, 2011) and SidePak (Thorpe, 2007; Zhu et al., 2007; Jiang, et al., 2011; TSI Inc., 2013) photometric aerosol monitoring instruments have indicated a significant overestimation of the particulate concentrations when compared to a reference gravimetric method. These studies were all conducted in various settings and compared to different reference methods. It is therefore critical to estimate a calibration factor for each monitor within the specific sampling environment.

The aim of this study was to evaluate and obtain a photometric correction factor for two indoor photometric monitoring instruments, DustTrak II Model 8530 and SidePak AM510, situated within a South African low-income settlement prone to the indoor combustion of low-grade solid fuels, such as coal and wood.

Material and Methods

Experimental Design

The results presented in this article are part of a larger study on the measurements of ambient and indoor exposures experienced in a typical low-income settlement in South Africa. KwaDela (26°27'47.53"S; 29°39'51.73"E) is such a low-income settlement located in the Mpumalanga Highveld, part of the Highveld Priority Area, approximately 200 km South-East of Johannesburg.

The settlement is somewhat isolated, the closest town being Bethal, which is ~25 km West of KwaDela. A significant proportion of the settlement relies on the burning of solid fuels as their primary energy source used for everyday activities such as space heating and cooking. An evaluation of indoor PM_4 has been done for a one week period in August 2014. During the sampling period ambient air temperatures averaged around 12°C (low 3°C, high 25°C) while an average relative humidity of 64% was experienced.

From these twenty sampling houses two were randomly selected for the comparison study. The PM_4 measurements were collected by making use of both photometric direct-reading instruments and a gravimetric sampling method.

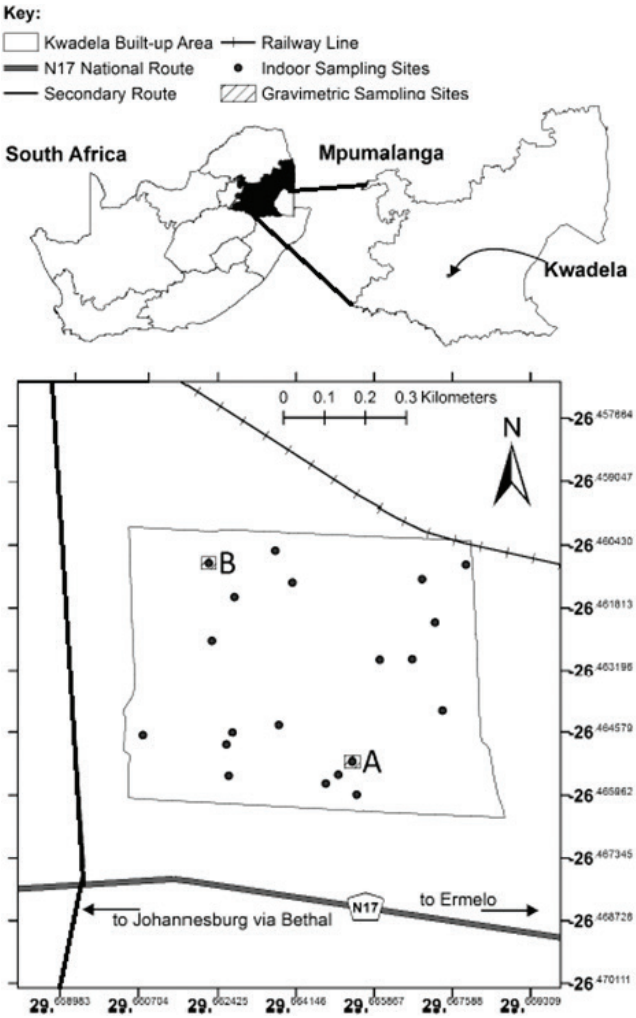

***Figure 1**: KwaDela low-income settlement in Mpumalanga, South Africa. The spatial distribution of the indoor and gravimetric sampling sites are also represented.*

Continuous Monitoring Instruments

PM_4 concentrations in indoor air has been measured using two photometric light scatting monitors, namely the **DustTrak II Model 8530** and **SidePak AM 510** (TSI Inc., Shoreview, MN, USA). These instruments do not have a built in PM_4 impactor, thus a **10-mm Nylon Dorr Oliver Cyclone** inlet (TSI Inc., Shoreview, MN,

USA) was used with each instrument. The instruments were sampled at a flow rate of 1.7 L.min^{-1}, to acquire the required 50% cut size at 4 µm (the cyclone removes 100% of 10 µm particles and 50% of 4 µm particles, this in turn resembles the 0% of 10 µm particles and 50% of 4 µm particles which enter the lung (Sensidyne, 1999)). The DustTrak operated for 24 hours a day, in 12 hour intervals from 10h00 to 22h00 and again from 22h00 to 10h00. The SidePak operated for 12 hours a day, in 6 hour intervals from 10h00 to 16h00 and again from 16h00 to 22h00.

These specific sampling times were chosen as to avoid a sample collecting PM over both peak burning period found in the settlement; which could result in filter overloading. PM_4 concentrations were logged in five minute intervals. The output for the particulate mass concentration was given in milligram per cubic meter (mg.m^{-3}) (TSI Inc., 2002; Kim et al., 2004; TSI Inc., 2014). By averaging the five minute interval concentrations over the sampling duration, the time-integrated measurement were calculated (Kim et al., 2004). Data was downloaded from the instruments at the end of each sampling event, by connecting the instrument via a USB connection to a computer, using the TSI TrackPro Software. Table 2 gives the manufacturer's specification for both the DustTrak and the SidePak photometric monitoring instruments.

***Table 2**: Manufacturer specifications for the photometric instruments*

	DustTrak II 8530	**SidePak AM510**
Flow Rate (L/min)	1.7-2.4 (1.7)	0.7-1.8 (1.7)
Particle Size Range (µm)	0.1 - ±10	0.1 - ±10
Mass Concentration Range (mg/m^3)	0.001-100	0.001-20
Laser Beam Wavelength (nm)	780	670
Operating Temperature (°C)	0 - 50	0 - 50
Temp. Coefficient (mg/m^3 per °C)	+0.001	+0.0005
Zero Stability (mg/m^3) over 24-hr at 10 second time-constant	±0.001	±0.001
Calibration	Arizona Test Dust	Arizona Test Dust

Source: TSI Inc. (2002 & 2014).

Gravimetric Sampling Method

The gravimetric sampling was done by exposing 37mm cassettes, at a constant flow rate of 1.7 L.min^{-1}, using Gilian GilAir 3 (Sensidyne, Clearwater, FL, USA) pumps. The pumps were fitted with 10-mm Nylon Dorr Oliver Cyclone inlets to obtain the 50% cut size at 4 µm. The gravimetric sampling occurred in line with the photometric monitors. Thirty-seven millimetre Borosilicate Microfiber Filters (ADVANTEC MFS Inc., Pleasanton, CA, USA), used in the 37 mm cassettes, were weighed prior to and after sampling. Weighing was done by making use of a XP26 DeltaRange Microbalance (Mettler-Toledo AG, Greifensee, CH) having a sensitivity of 1µg.

Photometric Calibration Factor

The PM_4 photometric measurements could be adjusted by making use of a calibration factor to approximate the actual PM_4 mass concentration. By doing a comparison between the PM_4 mass concentrations obtained from the photometric monitors and the reference gravimetric method a specific calibration factor was developed for each instrument. The calibration factor was calculated by the following equation (4):

$$Cal.Factor = \frac{Grav.Conc.}{Inst.Conc.}(Cur.Cal.Fac.) \qquad (1)$$

The DustTrak and SidePak measurements were then corrected by multiplying the five minute averages with the specific photometric calibration factor assigned to each instrument.

Quality Assurance and Quality Control

Various procedures were integrated into the sampling to ensure the quality of the photometric measurements. Preceding the start of the sampling campaign the monitors were sent for factory calibration using the respirable fraction of standard ISO 12103-1, A1 Arizona test dust. Before each sampling event the instruments were zero-calibrated by attaching the zero-filter as per the manufacturer's instructions. Flow rates were checked prior to and after each sampling event to ensure that the target flow rate was maintained. Filters were handled with care during weighing and loading activities as to prevent contamination and loss of gained PM and insure filter weight accuracies. The micro-balance was situated in a clean-lab, having controlled access, to limit external interference during weighing. The balance was levelled and calibrated, with the weights provided by the manufacturer, prior to each weighing session. It also has an internal function that removes any static that might influence the mass measurements.

Statistical Analysis

Basic statistical analyses were performed by using STATISTICA version 12 (StatSoft Inc.). All statistical analyses were performed with a 0.95 confidence and a 0.05 significance. The correlation coefficient analyses was performed to indicate the direction and strength of the linear relationship between the concentrations obtained from the real-time photometric instruments and gravimetric sampling. Furthermore, comparisons were made between initial and corrected PM_4 mass concentrations (one day case study) as well as cumulative distributions for a one week period.

Results and Discussion

Photometric Calibration Factors

Twenty-eight sets of comparison samples were collected during a week sampling in August 2014. A total of seventeen sets were valid, eight sets contributing to the evaluation of the DustTrak and nine to the evaluation of the SidePak. The other eleven sets were voided due to the loss of filter mass during gravimetric sampling (8), SidePak monitor experiencing a battery failure (1), and incorrect flow rates (2).

The linear regression for the 12-hour integrated DustTrak concentrations against the 12-hour gravimetric concentration

resulted in a correlation coefficient (r^2) of 0.79, which gives an indication that the DustTrak measurements have a strong positive correlation when compared to the gravimetric concentrations. The linear regression for the 6-hour integrated SidePak concentrations against the 6-hour gravimetric concentration data resulted in a correlation coefficient (r^2) of 0.64, indicating a moderate positive correlation. In addition, an analysis was done of the ratio of the 12-hour integrated DustTrak concentrations and 6-hour integrated SidePak concentrations against the 12- and 6-hour gravimetric concentrations. The median ratio value for the DustTrak is 11.54 (low 3.76, high 31.25) with a standard deviation of ±9.23, while the median ration value for the SidePak is 3.83 (low 1.11, high 19.80) with a standard deviation of ±6.49. An average ratio of 7.32 and 4.16 existed between the DustTrak and SidePak and their respective gravimetric concentration. The ratios for the both these instruments vary dramatically from one day to the next. This may indicate that there is a significant variation in the day-to-day variability within a single household.

The estimated photometric calibration factor for the DustTrak is 0.14 (**95%Cl**: 0.09, 0.15) whereas the SidePak has an estimated calibration factor of 0.24 (95%Cl: 0.16, 0.30). The DustTrak calibration factor is significantly lower than those produced by previous studies. The SidePak calibration factor, while not identical to previous studies is slightly lower. The differences could be due to various aspects such as (1) having a reduced sensitivity when measuring lower PM concentrations (Jimenez et al., 2011), (2) the variations in chemical composition of aerosols and the type of aerosol (Jiang et al., 2011), (3) the difference in density between Arizona test dust and the type of aerosol measured, combustion aerosol tend to have a lower density than the test dust (TIS Inc., 2013), (4) the effect of temperature and relative humidity (McNamara et al., 2011), and (5) the different size fractions associated with aerosols (Yanosky et al., 2002).

Cumulative Distribution

The initial and corrected PM_4 data shows the cumulative exceedances (Table 3) of all WHO and NAAQS standards are similar for both the DustTrak and SidePak instruments. Initial (DustTrak and SidePak) measurements exceed the 75 µm/m^3 NAAQS PM_{10} level for 35% and 28% of observed measurements, while the corrected measurements exceed the level for 5% of the observed measurements. The highest level of cumulative exceedances are of the 25 µm/m^3 WHO $PM_{2.5}$ level. This level is exceeded for 92% and 100% of the observed measurements, while the corrected measurements exceed the level for 10% and 18% of the observed measurements.

***Table 3**: Summary of the cumulative exceedances of PM_4 observed measurement concentrations for a one week period*

24 Hour (µg/m^3)	DustTrak Model 8530		SidePak AM510	
	Initial	Corrected	Initial	Corrected
WHO $PM_{2.5}$	92%	15%	**100%**	18%
WHO $PM_{2.5}$	65%	8%	**68%**	10%
NAAQS $PM_{2.5}$	42%	6%	**35%**	6%
NAAQS PM_{10}	35%	5%	**28%**	5%

Conclusion

Due to the linear relationship between negative health effects and increased PM concentrations, this observation indicates that the residents within KwaDela are chronically exposed to high levels of PM_4.

The development of a PM_4 calibration factor for an indoor environment prone to the combustion of solid fuels, such as coal and wood, has implications for both scientific and regulatory studies especially with regard to epidemiological and exposure assessments.

Historically, researchers have made use of averaged 24-hour values to characterise and estimate exposures to PM levels. It is, however, possible to measure exposures over short-term periods by making use of real-time PM monitors. Light-scattering photometer instruments are advantageous to use for monitoring indoor PM_4 concentrations due to the fact that they provide real-time data giving us insight into short-term changes in exposure levels. These instruments are also portable and require that minor maintenance be done periodically, making it easy to deploy within an indoor monitoring network, especially one within a low-income settlement such as KwaDela. The estimation of calibration factors for indoor solid fuel combustion reinforces certainty in studies that utilise these real-time monitoring instruments intended for this purpose.

A specific calibration factor was estimated for the DustTrak (0.14) and SidePak (0.24). These calibration factors should primarily be utilised where DustTrak and SidePak monitoring is conducted to quantify PM_4 exposure within an indoor environment where solid fuel combustion takes place.

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Influence of coal-particle size on emissions using the top-lit updraft ignition method

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Abstract

Despite the Government's intervention of an intensive electrification program in South Africa, which has resulted in more than 87% of households being connected to the grid, a majority of low-income households still depend on solid fuel (coal and wood) as a primary source of energy, especially on the central Highveld. In informal settlements, combustion of coal is done in inefficient self-fabricated braziers, colloquially known as imbaulas. Emissions from domestic coal combustion result in elevated household and ambient air pollution levels that often exceed national air quality limits. Continued dependence on coal combustion exposes households to copious amounts of health-damaging pollutants. Despite the health significance of coal-burning emissions from informal braziers, there is still a dearth of emissions data from these devices. Consequently, evaluating the emission characteristics of these devices and to determine the resultant emission factors is needed. The effects of ignition methods and ventilation rates on particulate and gaseous emission from coal-burning braziers are reported in literature. However, to date there are no studies carried out to investigate the influence of the size of coal pieces on brazier emission performance. In this paper, we report on controlled combustion experiments carried out to investigate systematically, influences of coal particle size on gaseous and condensed matter (smoke) emissions from informal residential coal combustion braziers. Results presented are averages of three identical burn-cycles of duration three hours or fuel burn-out, whichever was the soonest.

Keywords

coal particle size; brazier; imbaula, emission factor, smoke

Introduction

Energy is an important factor for economic growth, community development and sustenance of life in South Africa (Masekameni et al., 2014). Globally, more than 3 billion people rely on solid fuels combusted in open fires or traditional stoves, for purposes of cooking and space heating (Smith et al., 2012). Emissions from solid fuels account for 4.3 million deaths per year globally (Gordon et al., 2014). These deaths are more common in developing countries with South Africa being no exception (WHO, 2012). It is argued that these deaths can be reduced by use of cleaner burning cook stoves and the introduction of efficient ignition methods that lead to low emissions (Masekameni et al., 2015).

More than half of the South African population still depend on coal and wood for cooking and space heating needs (Kimemia et al., 2011). In the low to medium economic stratum, these fuels are burnt in inefficient stoves and open fires that do not allow for complete combustion, thus impacting on human and environmental health (Kimemia et al., 2011). In the central Highveld of South Africa, a majority of low-income households burn coal and wood in self-fabricated braziers known colloquially as *imbaulas*, which are constructed from discarded steel drums (Kimemia, 2010). The braziers have holes punched around the sides to provide primary air needed for combustion. These devices are used extensively in winter resulting in severe indoor and ambient air pollution (Makonese et al., 2015). The use of poor quality coal in these devices, results in high emissions of gaseous and particulate matter (Makonese et al., 2014a). Coal fuel commonly used in informal settlements of South Africa is the untreated bituminous coal with ash content of up to 40% and with energy content between 15 and 25 MJ/kg (Annegarn & Sithole, 1999; Pemberton-Pigott et al., 2009).

Smith et al (2014) contends that the continued use of coal in poorly ventilated and inefficient stoves leads to increased exposure to health damaging pollutants and the development of respiratory diseases. Bruce et al (2000) found that 1300 lives, amongst children below the age of five are lost each year due to excessive inhalation of particulate matter from domestic

coal combustion between the years 1995-2000 in developing countries. Annegarn and Sithole (1999) reported that these stoves lack performance improvements resulting in increased emissions of particulates and gases.

To reduce emissions of noxious gases and particulate matter, existing or new braziers should be optimised. Optimisation of solid fuel burning appliances should consider stove design parameters (i.e. number and distribution of holes above and below the fire grate, the position of the grate in the bucket), fuel characteristics (such as fuel particle size and fuel quality), and operational practices (including ignition methods and fire tending practices) (Makonese, 2015; Masekameni et al., 2014). For example, the top-lit updraft (TLUD) ignition method has been reported to be an effective way of igniting a fire in a coal brazier. A coal fire ignited using the top-lit updraft (TLUD) method produces less visible smoke compared to a fire ignited using the conventional/traditional method. This TLUD ignition method has become a national priority energy intervention programme due to its estimated 80% reduction in ambient particulate air pollution and 20% reduction in coal use at no additional cost (Makonese et al., 2014b).

The effects of ventilation rates (as a function of the size and distribution of holes around the brazier), coal quality, and ignition methods on emissions of gases and particulates from coal burning braziers are reported in literature (Makonese, 2015; Makonese et al., 2014b). However, there are still limited studies carried out to investigate the influence of the size of coal pieces on brazier emission performance.

In light of the above, this study aims to investigate the influence of coal particle size on the emissions performance of coal-burning braziers using the top-lit updraft method. In this paper, three coal particle sizes are evaluated for emission factors of carbon monoxide (CO_{EF}), CO/CO_2 ratio and $PM_{2.5}$ emission factors, using a high ventilation laboratory designed brazier.

Methodology

Fuel Preparation

D-grade coal from Slater mine in Mpumalanga was chosen for our experiments. The fuel is preferred by local coal merchants. Three different coal particle sizes ranges 20 – 40 mm (small), 40 – 60 mm (medium) and 60 – 80 mm (large) were used to investigate emissions performance in a high ventilation rate (i.e. measured as a function of the number and size of air holes on the sides of the brazier) brazier. Large coal nuggets were crushed into small pieces before sieving them through a 20 x 40 mm wire sieve for the 20 – 40 mm size range for small coal size.

For medium size, coal was sieved through a 40 x 60 mm wire mesh, while for large coal size a 60 x 80 mm sieve was used. In order to ensure that the correct sizes were obtained in each category, the technicians checked the dimensions of a sample of already sieved individual coal particles using a ruler. 4 000 g of selected coal fuel were used for each size category.

Coal analysis

The coal was characterized for thermal content, major elemental (proximate) analysis, moisture and ash content by an independent laboratory (Bureau Veritas Inspectorate Laboratories (Pty) Ltd). The fuel samples were analysed on an air-dried basis. Experimental results presented in this paper are based on the proximate and ultimate analysis results for the D-grade coals used in making the fires. Fuel specifications used during the experiments are provided in Table 1.

***Table 1**: Fuel analysis*

Parameter (Air Dried Basis)	Standard Method	Slater Coal D-Grade
Moisture content (%)	ISO 5925	3.5
Volatiles (%)	ISO 562	20.3
Ash (%)	ISO 1171	24.2
Fixed carbon (%)	By difference	52.0
Calorific value (MJ kg^{-1})	ISO 1928	23.4
Calorific value (Kcal kg^{-1})	ISO 1928	5590
Total sulphur (%)	ASTM D4239	0.63
Carbon (%)	ASTM D5373	62. 6
Hydrogen (%)	ASTM D5373	2.72
Nitrogen (%)	ASTM D5373	1.43
Oxygen (%)	By difference	4.96

Choice of fire-ignition methods

The TLUD ignition method was used to investigate the influence of coal particle size on emissions of carbon monoxide and particulate matter, and the CO/CO_2 ratio.

The order of laying a fire during a top-lit ignition fire entailed the following: first, placing the major portion of the coal load on the support grid in the brazier, then paper and wood kindling, with a few lumps of coal added at an appropriate time after the fire has been lit. In our experiments, 3 000 g of coal was added to the bottom of the brazier onto the fuel grate. 36 g of paper and 450 g of kindling were added. After igniting the kindling, ~1 000 g of coal was added to the brazier above the kindling.

Tests were conducted under controlled laboratory conditions, keeping parameters such as ignition method and ventilation rates constant.

Stove characterisation

The brazier used in our experiments is shown in Figure 1. The brazier has a fuel support grate, made of wire although it is common to have some braziers operated without a fire grate. With a fire grate in place the rate of burning is increased. It should be noted that there is no standard brazier, as the devices vary greatly in terms of the number and sizes of the side holes (i.e. affecting ventilation rates), the presence of a grate and its position in the metal drum (Kimemia et al., 2011).

Ventilation rates affect the overall performance of the stove and these rates differ significantly from one device to the other. To evaluate realistically and compare the performance of two or more braziers, ventilation rates need to be specified. Ventilation rates for the experimental brazier used in the study are given in Table 2.

***Figure 1**: Brazier ignited using the TLUD ignition method*

***Table 2**: Stove description*

Brazier type	Height (mm)	Dia. (mm)	Grate height (mm)	Area of holes below grate (cm²)	Area of holes above grate (cm²)
High ventilation	370	290	185 (50%)	248 (61%)	159 (39%)

Test apparatus

The hood method was used for evaluating emissions (Ahuja et al., 1987). The gas samples were analysed using two Testo® flue gas analysers model (Testo® 350XL/454). The sampling configuration for the undiluted flue gases included, in sequence, a stainless steel tube, a filter holder, and a flue gas analyser. For the diluted channel, the sampling configuration included, in sequence, the dilution system, a Teflon tube channel, and a second Testo® flue gas analyser. Traditional coal stoves (*Imbaulas*) emit high levels of particulate emissions; therefore, the dilution system was used to maintain aerosols emissions within the detection limit of the instrument (150 mg/m^3). The Testo® measures Carbon dioxide (CO_2), Carbon monoxide (CO), Nitrogen oxides (NO_x), Nitrogen dioxide (NO_2), Hydrogen (H_2), Sulphur (S), Sulphur dioxide (SO_2) and Oxygen (O_2).

Particle mass concentrations and size segregated mass fraction concentrations were monitored using a DustTrak DRX 8533 aerosol monitor. The DustTrak DRX Model 8533 is a laser-based instrument that measures size fractions of the sampled aerosol, from which mass fractions are deduced. The instrument simultaneously measures size segregated mass fraction concentrations (i.e. PM_1, $PM_{2.5}$, PM_4, PM_{10}, and Total Particle Mass - TPM) over a wide concentration range (0.001–150 mg/m^3) in real time. Data points were recorded at 10 s intervals.

Testing apparatus

A schematic description of the sampling train is shown in Figure 2. Section A in the schematic show the mixing point, where raw exhaust sample mixes with compressed air. The diluted sample was drawn at point B. A raw exhaust sample was collected at point C.

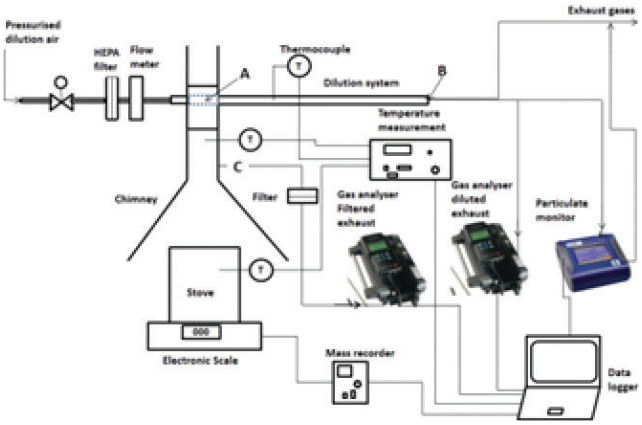

***Figure 2**: Schematic illustration of the experimental dilution set-up for the SeTAR dilution system, showing the mixing point (A) and the sampling diluted exhaust gas point (B) and sampling point (C) is for raw exhaust gases.*

Quality control

For each fuel/stove combination, a series of preliminary burn cycles were carried out to standardise procedures and to minimize the natural variability due to differences in operator behaviour. To familiarise the operators with the testing procedure and with the characteristics of the stove, these trial runs were conducted repeatedly until a stable mode of operation was established. Thereafter three definitive tests were conducted for each fuel/stove combination.

After each fuel/stove combination was tested, the probes were cleaned and the pumps and machines checked and zeroed (Makonese, 2015). Before tests were conducted, the sampling dilution system components were cleaned, assembled, and tested for leaks to prevent contamination from the surrounding air.

A calibration exercise was performed to check the accuracy of the flow rates through each of the critical flow orifices. The sampling dilution system was cleaned prior to testing to minimize pre-existing organic and metal compounds, including the use of high power compressed air and water to remove large particles.

The collection trains, including the stainless steel piping and sampling nozzles, were cleaned with soap, water-rinsed and then air-dried with compressed air. The dilution system was

then assembled and connected to the testing rig for a trial run of the tests.

Results

CO emission factors

Carbon monoxide emission factors (CO_{EF}) of the three coal particle sizes results are presented pairwise to compare between coal particle sizes in Table 3). Differences between CO_{EF} pairs are tested for significance using a student T-test, to indicate whether changes in coal particle size result in a significant difference in the emission factor.

A change in coal particle size did not cause a significant difference on the CO_{EF} for the small (20 – 40 mm and medium (40 – 60 mm) particle sizes. However, there is a significant difference in CO_{EF} between medium (40 – 60 mm) and large (60 – 80 mm) coal particles sizes. Results show that there also are significant differences in CO_{EF}, at the 95% confidence level, between small (20 – 40 mm) and large (60 – 80 mm) coal particle sizes. The CO_{EF} for large coal pieces is about three fold higher than for medium and low pieces.

***Table 3**: CO_{EF} of three coal particle sizes in a high ventilation stove using TLUD ignition method*

Coal particle size	Ignition method	CO_{EF} (g/MJ) (n = 3)	Statistical analysis		
			F-Test	P-Value	Sig @ 95%
Medium vs Small	TLUD	1.6 ± 0.09 1.5 ± 0.04	0.31	0.07	No
Large vs Medium	TLUD	4.3 ± 0.22 1.6 ± 0.09	0.31	<0.01	Yes
Large vs Small	TLUD	4.3 ± 0.22 1.5 ± 0.04	0.07	<0.01	Yes

CO/CO_2 ratio over the Burn Cycle

Results of the influence of coal particle sizes on CO/CO_2 ratio are shown in Table 4, for the three different coal particle sizes. There are no significant differences in the CO/CO_2 ratio between small and medium coal particle sizes. However, pairwise comparison between medium and large coal particle sizes indicated a significant difference at the 95% confidence level.

Increasing coal particle size ranges from 20 – 40 mm to 60 – 80 mm, leads to an increase in the CO/CO_2 ratio by ~ 65%. The nominal combustion efficiency is reduced from 97.5% to 92.6%. These results are expected – larger coal particle sizes burn poorly relative to small and medium coal particle sizes.

***Table 4**: Pairwise comparison by coal particle size of average CO/CO_2 ratio over the burn cycle*

Coal particle size	Ignition method	CO/CO_2 ratio [%] (n = 3)	Statistical analysis		
			F-Test	P-Value	Sig @ 95%
Medium vs Small	TLUD	2.5 ± 0.51 2.8 ± 0.22	0.29	0.39	No
Large vs Medium	TLUD	7.4 ± 0.66 2.5 ± 0.51	0.75	<0.01	Yes
Large vs Small	TLUD	7.4 ± 0.66 2.8 ± 0.22	0.19	<0.01	Yes

$PM_{2.5}$ Emission Factors

Results of pairwise comparison of average $PM_{2.5}$ emission factors over the burn cycle of the three coal particle sizes are presented in Table 5. There are no significant differences in $PM_{2.5}$ emission factors between medium and small coal particle sizes. Pairwise comparison between large and medium coal particle sizes resulted in a significant difference in $PM_{2.5}$ emission factors. A similar result is observed between large and small coal particle sizes. Reducing coal particle size ranges from 60–80 mm to 20–40 mm leads to a 50% reduction in $PM_{2.5}$ emission factors.

***Table 5**: Pairwise comparison by coal particle size of average $PM_{2.5EF}$ over the burn cycle*

Coal particle size	Ignition method	Avg. $PM_{2.5}$ (g/MJ) (n = 3)	Statistical analysis		
			F-Test	P-Value	Sig @ 95%
Medium vs Small	TLUD	0.31 ± 0.02 0.42 ± 0.06	0.29	0.39	No
Large vs Medium	TLUD	0.75 ± 0.04 0.31 ± 0.02	0.75	<0.01	Yes
Large vs Small	TLUD	0.75 ± 0.04 0.42 ± 0.06	0.19	<0.01	Yes

$PM_{2.5}$ concentration time series plots over the burn cycle

Time series plots of $PM_{2.5}$ concentrations are shown in Figure 2, for the three coal particle sizes. All three-coal particle sizes experienced high peaks at ignition as the kindling burned and consequently ignited the coal. The $PM_{2.5}$ concentration drops sharply within a few minutes, and then peaks again during pyrolysis phase.

The small and medium coal particle size indicates an earlier ignition of the main fuel bed relative to larger coal size range, indicated by lower $PM_{2.5}$ emissions 30 minutes after ignition (Figure 3). The largest coal size bed (with 80 mm coal particles) takes over 90 minutes to drive off most of the PM and is characterised by an unsteady burn rate. This result is similar to that of Yang et al (2005) who reported that a larger particle-size bed tends to burn more transiently compared to a smaller particle-size bed, which tends to quickly build up to a steady burn pattern. This suggests that the control of a brazier burning larger coal particle sizes needs to be more carefully planned because of the constant variation of the burn pattern as a function of the fuel size (Yang et al., 2005).

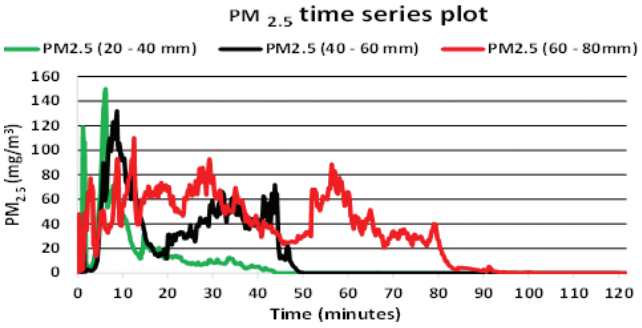

***Figure 3**: $PM_{2.5}$ time series plots for the three coal particle sizes in a high ventilation stove*

In summary, evidence presented shows that coal particle size ranges have an influence on gaseous and particulate emissions from coal braziers. Large coal particle sizes result in poor combustion efficiencies and increased CO and $PM_{2.5}$ emissions. It is recommended that coal particle size ranges of between 20–40 mm be used for optimal brazier performance.

Significance and conclusion

In general, the following conclusions can be drawn from this study. Particulate and CO emission factors increase with an increase in the mean size range of the fuel. Small and medium coal particle sizes produced comparable emissions (CO and $PM_{2.5}$) and CO/CO_2 ratio. The ignition time and the time to reach full pyrolysis are shorter with a bed of smaller particles compared to a bed of larger particles, when the devices are operated under the same conditions. Small coal particle size ranges presented a uniform flame propagation speed for most parts of the combustion process, while large particles showed a less stable transient features where the burning rate, although lower compared to small coal particle sizes, fluctuates throughout the combustion process.

If these results are validated by further testing using stoves with medium and low ventilation rates, as found within the range of artisan manufactured braziers, it would imply that pollution reductions can be achieved by supplying a regulated graded coal size, in the range 20–40 mm, to the domestic coal market. However, small coal particles burn quicker and therefore more of the fuel will be required to complete any given task, leading to an increased financial burden on the user.

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Assessment of ambient air pollution in the Waterberg Priority Area 2012-2015

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Abstract
The Waterberg Priority Area ambient air quality monitoring network was established in 2012 to monitor the ambient air quality in the Waterberg Air Quality Priority Area. Three monitoring stations were established in Lephalale, Thabazimbi and Mokopane. The monitoring stations measure the concentrations of PM_{10}, $PM_{2.5}$, SO_2, NO_x, CO, O_3, BTEX and meteorological parameters. Hourly data for a 31 month period (October 2012-April 2015) was obtained from the South African Air Quality Information System (SAAQIS) and analysed to assess patterns in atmospheric concentrations, including seasonal and diurnal patterns of the ambient concentrations and to assess the impacts that such reported pollution concentration may have. Local source regions for SO_2, PM_{10}, $PM_{2.5}$ and O_3 were identified and trends in the recorded concentrations are discussed.

Keywords
Waterberg Priority Area, Air Pollution, PM_{10}, $PM_{2.5}$, SO_2, O_3

Introduction
The Waterberg coal fields extend across the border between South Africa and Botswana. These coal fields are estimated to hold a reserve of approximately 6Gt (6×10^9 Mg). This coal reserve is regarded as the last remaining large coal resource in the country (Hartnady 2010). As such, in the National Development Plan (National Planning Commission 2010), the Waterberg coal fields have been earmarked for further industrial development, related to exploitation of the coal resource for *inter-alia* power generation.

Due to the expected development within the Waterberg Area and the existing mining and metallurgical activities in the western arm of the bushveld igneous complex (Venter et al. 2012), there is concern regarding the future and current air quality in these regions. As a result the Waterberg District Municipality (Limpopo Province) and the Bojanala Platinum District Municipality (North West Province) were declared as the Waterberg Priority Area in 2012 since the Minister of Environmental Affairs expected the levels of pollutants in the Waterberg District to exceed the National Ambient Air Quality Standards (NAAQS) (DEA 2009) in the near future and that a significant trans-boundary situation exists between the Waterberg District Municipality in Limpopo Province and the Bojanala Platinum District Municipality in the North-West Province (Department of Environmental Affairs 2012) (Figure 1). A draft air quality management plan has been developed which details the major pollutant sources and receptors (Department of Environmental Affairs 2014).

A number of studies in ambient air pollution have been conducted in the past. A passive sampling network was operated over the northern parts of South Africa between 2005 and 2007 (Josipovic et al. 2010). This study reported occasional high concentrations of SO_2 at Thabazimbi and Mokopane, The source of the SO_2 at Thabazimbi was attributed to the Thabazimbi iron ore mine and smelter, the Matimba power station and the Grootgeluk coal mine in Lephalale. The elevated levels of SO_2 at Mokopane were attributed to the Mokopane platinum mine and the Matimba power station.

A long term air quality measurement campaign was conducted in the Bojanala District of the Waterberg Priority area (Venter et al. 2012). This campaign took place at Marikana from February 2008 to May 2010. In the Venter et al. 2012 study it was reported that the concentrations of NO_x , SO_2 and CO were within the NAAQS but there were significant exceedances of the standards for ozone and particulate matter. It was also within this region that Hirsikko et al. 2012 reported a high frequency of new particle formation events and an average particle number concentration of $10^4/cm^3$. They further postulated that SO_2 was the likely feed material for the new particle formation.

Due to the known and expected future exceedances of the NAAQS in the Waterberg Priority Area, it was necessary to establish an

ambient air quality monitoring network, to monitor the ambient concentrations of criteria pollutants in the area. This study examines the first two and a half years of the monitoring results for the three ambient air quality stations in the Waterberg Priority area. This study intends to characterise the spatial and temporal patterns in criteria pollutant concentrations, and to identify potential pollutant sources.

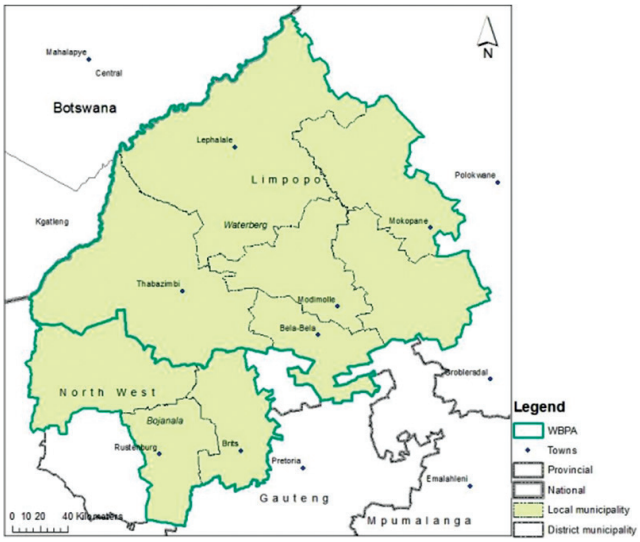

Figure 1: *Waterberg Priority Area (Department of Environmental Affairs 2014)*

Methods

Three ambient air quality monitoring stations were established in the Waterberg Priority Area in October 2012. The stations are located at Thabazimbi, Lephalale and Mokopane (Figure 1).

Each of the stations is fully equipped to monitor the following parameters at a temporal resolution of 1 minute:

- Sulphur Dioxide (SO_2)
- Particulate matter of aerodynamic diameter >10 um (PM_{10})
- Particulate matter of aerodynamic diameter > 2.5um ($PM_{2.5}$)
- Oxides of Nitrogen (NO_x = NO + NO_2)
- Ozone (O_3)
- Carbon Monoxide (CO)
- VOCs (Benzene, Toluene, Ethyl benzene, Xylene)
- Meteorological Parameters
  - Wind Speed
  - Wind direction
  - Pressure
  - Temperature
  - Relative Humidity
  - Solar Radiation
  - Rainfall

Data from the monitoring stations reports in real time to a server located at the South African Weather Service. On a monthly basis the data was assessed and validated to remove spikes and calibration data and to adjust drifts in the data.

Daily checks were performed on the stations by remotely accessing the data logging system, if problems with the station were identified non-routine maintenance was carried out. On a bi-weekly basis routine site visits were conducted to ensure that the instrumentation was functioning and to perform a zero and span (80% of instrument maximum) check using NMISA certified calibration gases to ensure that the drifts and deviations of the instrument were within the specified ranges, if the instrumentation was found not to respond within the data quality criteria the data was flagged and corrected or removed from the dataset. On a quarterly basis multipoint calibration verifications (zero, 80% of instrument range and three intermediate points) were conducted utilizing NMISA certified reference gases. A full calibration of all the instruments was conducted on an annual basis by a South African National Accreditation System (SANAS) accredited calibration laboratory.

Table 1*: Station location and monitoring purpose*

Latitude	Longitude	Data Recovery October 2012-April 2015	Monitoring purpose
Lephalale			
S23.681	E27.722	85.0%	Impact on human health in a low income residential community impacted by domestic combustion, vehicular emissions, biomass burning, the Grootgeluk coal mine and the Matimba power station. Future impacts from Medupi coal fired power station are expected.
Thabazimbi			
S24.591	E27.391	80.8%	Located in a low income residential community, domestic combustion, biomass burning, vehicular and road emissions and iron ore mining activity.
Mokopane			
S24.155	S24.155	85.9%	Human health impacts in a low income residential area, impacted by domestic combustion, vehicular and road emissions and small scale industry as well as biomass burning.

For this study hourly averaged data for SO_2, PM_{10}, $PM_{2.5}$ and O_3 were extracted from the South African Air Quality Information System (SAAQIS) and revalidated to remove negative concentrations and data spikes that were not removed during the original validation. A data completeness rule of 80% was used for data averaging to the hourly average that was utilised and any subsequent averaging. The data was assessed using the Open Air Package in R (Uria-Tellaetxe and Carslaw 2014; Carslaw 2014).

Results and Discussion

The monitoring data from the three monitoring stations were assessed to characterise the atmospheric dynamics of the site, including the diurnal and seasonal cycles and the potential pollutant sources. The results are presented for the four criteria pollutants of greatest concern in South Africa, namely sulphur dioxide (SO_2), particulate matter (PM_{10} and $PM_{2.5}$) and ozone (O_3) (Thompson et al. 2011; Lourens et al. 2011; Venter et al. 2012).

Sulphur Dioxide

The concentration of SO_2 at the monitoring stations is presented in Table 2. The ambient SO_2 concentrations over the period are low with mean values in the range of 1-1.5ppb. The 90 percentile at all the stations does not exceed 5ppb. In comparison the annual National standard is 19ppb. Compliance with the national standards is presented in the National State of the Air Report.

***Table 2**: SO_2 measurement summary*

	Lephalale	Makopane	Thabazimbi
N	21280	20053	21250
% recovery	95.1%	86.8%	95.0%
Mean	2.19	1.68	2.14
Median	0.82	0.97	1.11
10 percentile	0.278	0.45	0.38
25 percentile	0.48	0.64	0.63
75 percentile	1.7	1.82	2.25
90 percentile	3.30	3.56	4.52

The relation between the concentration of SO_2 and wind speed and direction is presented in Figure 3. The Lephalale plot shows a hotspot of SO_2 associated with low to medium speed winds from the westerly and north westerly sectors. This corresponds to the location of the Matimba power station and the Grootgeluk coal mine which are likely the source of the SO_2.

The monthly trend of the SO_2 concentrations at the monitoring stations is presented in Figure 4. Of the three stations only Mokopane showed a statistically significant trend in the SO_2 concentrations. At Mokopane the SO_2 concentration decreased at a rate of 0.3ppb per year (P> 0.001). The decrease at the Mokopane station appears to have occurred from late 2013 or early 2014. The SO_2 concentrations at Lephalale and Thabazimbi did not show any statistically significant trends.

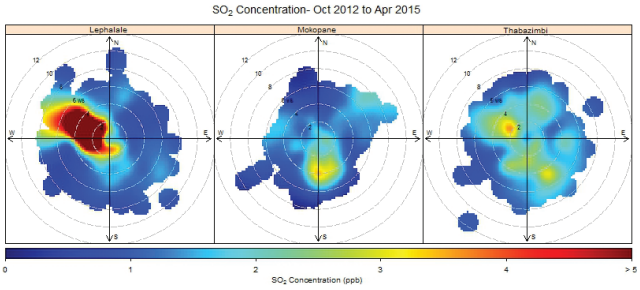

***Figure 2:** Polar Plot of the SO_2 concentration at the Waterberg monitoring stations*

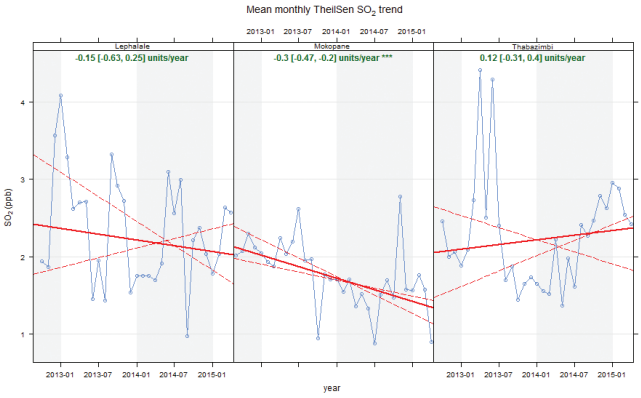

***Figure 3:** Monthly Mean Deseasonalised SO_2 Trend, for the period Oct 2012-April 2015. The solid trend line represents the mean slope of the trend, while the dashed trend lines represent the 95% confidence interval of the slope*

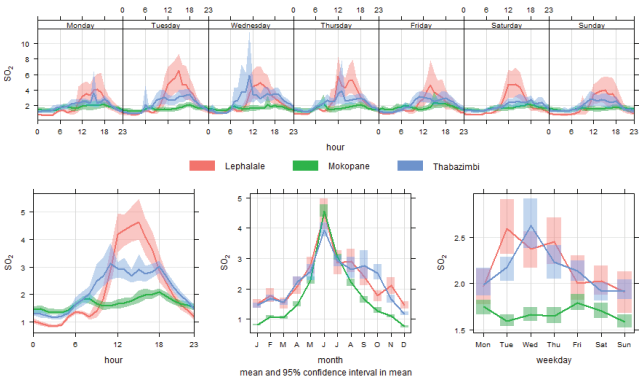

***Figure 4:** SO_2 Time variation plot for the period October 2012 to April 2015*

The time variation in the hourly SO_2 concentrations is presented in Figure 5. It is shown that there is a strong diurnal profile in Lephalale and Thabazimbi, where there is a peak in the SO_2 concentrations during the day; this is typical of sites influenced by pollution from industrial stack emissions, which is brought to the surface during periods of high convection (Venter et al. 2012; Zhou et al. 2012) For the Lephalale site, the mid-day peak occurs throughout the week, which would correspond to a high level source that is emitting continuously. For the Thabazimbi site the largest SO_2 peak occurs on the Wednesday morning and may indicate a specific process that occurs on a weekly basis at one

of the facilities in the area. All three sites show a strong seasonal profile in the SO_2 concentrations, where the highest values are recorded during the winter months.

PM_{10}

The average PM_{10} concentration at the three Waterberg stations for the period October 2012- April 2015 was 52µg/m^3 for Thabazimbi, 40.6µg/m^3 for Mokopane and 26µg/m^3 for Lephalale (Table 3). The 90th percentile for the Thabazimbi and Mokopane stations is higher than 100µg/m^3. The average PM_{10} concentration over the 2.5 year measurement period (October 2012 to April 2015) is greater than the annual PM_{10} standard (40µg/m^3).

***Table 3**: PM_{10} measurement summary*

	Lephalale	Makopane	Thabazimbi
Number of measure-ments	20739	19608	15027
% recovery	92.68%	84.8%	67.2%
Mean	26.04	40.64	52.31
Median	19.11	26.93	30.93
10 percentile	5.94	8.60	8.01
25 percentile	11.03	14.88	16.52
75 percentile	32.95	50.64	59.46
90 percentile	53.37	87.48	115.62

When the relation between the PM_{10} concentrations and the wind speed and wind direction are considered (Figure 7) the periods of highest PM_{10} concentration correspond to periods of high wind speed, typically greater than 6m/s. These are periods when the high PM_{10} concentrations are likely to be attributable to the generation of windblown dust. Marticorena & Bergametti (1995) modelled the generation of aeolian dust based on threshold friction velocities, or the point at which the wind speed is high enough to entrain soil particles from the surface. This approach has successfully been used to model dust generation in other regions (Kocha et al. 2011; Schmechtig et al. 2011).

The trend in the PM_{10} concentrations seems to be decreasing in all three sites (Figure 8) where there is a decrease in the PM_{10} concentration of between 4.5 and 6.5 µg/m^3/year. This, however, is only statistically significant at the Lephalale site ($p<0.01$).

The seasonal, diurnal and day of week time variation plots for PM_{10} are presented in Figure 9. The PM_{10} concentrations show a distinct diurnal pattern at all stations, with peaks occurring in the morning (06:00) and in the evening (18:00). The evening peak is greater than the morning peak. This pattern holds for all the stations and is likely linked to domestic combustion or traffic sources. The seasonal cycle shows a strong peak during the winter months from April to October, which corresponds to the periods where there is increased atmospheric stability over the interior of the country (Preston-Whyte et al. 1976; Scott & Diab 2000; Lourens et al. 2011) increased biomass burning (Korontzi 2005) and domestic combustion for space heating (Wernecke et al. 2015) .

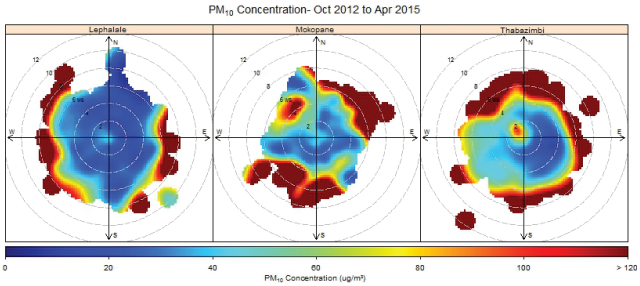

***Figure 5:** Polar Plot of the PM_{10} concentration at the Waterberg monitoring stations*

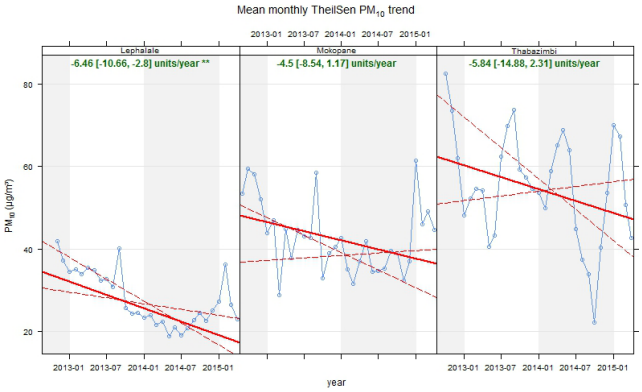

***Figure 6:** Monthly Mean Deseasonalised PM_{10} Trend for the period Oct 2012-April 2015 the solid trend line represents the mean slope of the trend, while the dashed trend lines represent the 95% confidence interval of the slope*

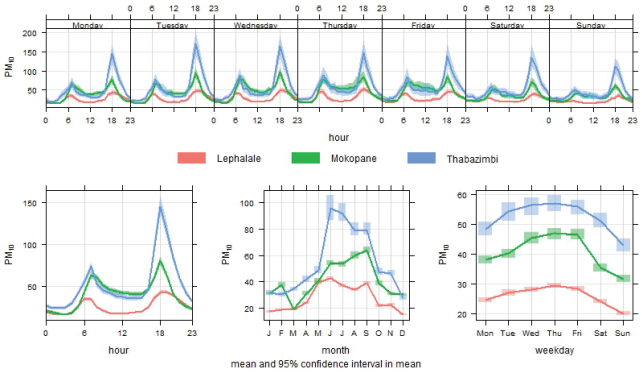

***Figure 7:** PM_{10} Time variation plot for the period October 2012 to April 2015*

A strong diurnal pattern in the PM_{10} concentrations was observed occurring in the early morning and in the evening. This is strongest at the Thabazimbi and Mokopane stations where the evening peak PM_{10} concentration is considerably greater than the morning peak. To further allude to the domestic combustion component of the PM_{10} source a day of week pattern was also observed at all the stations, with higher average PM_{10} concentrations being observed between Monday and Friday, followed by decreases on Saturday and Sunday, especially in the morning peak over the weekend. This could indicate that the behaviour patterns of the people in these areas changes over

the weekends and there is less vehicular traffic and the timing of activities may be more staggered than during the work week. For all the sites there is a strong contrast in the temporal profiles of PM_{10} and SO_2, indicating that these pollutants are generated at different sources.

$PM_{2.5}$

The mean $PM_{2.5}$ concentration at the three Waterberg monitoring stations ranges from 12.3µg/m³ for Lephalale to 20 µg/m³ and 20.3µg/m³ for Thabazimbi and Makopane respectively (Table 4). Thabazimbi and Mokopane showed the highest $PM_{2.5}$ values. For the 2.5 year monitoring period considered here the average $PM_{2.5}$ concentration at all the sites is below the national standard for the period of the measurement (25µg/m³), however for Mokopane and Thabazimbi it exceeds the stricter standard (20µg/m³) that came into effect at the beginning of 2016.

***Table 4**: $PM_{2.5}$ measurement summary*

	Lephalale	Makopane	Thabazimbi
Number of measure-ments	20743	19633	14687
% recovery	92.70%	85.0%	65.6%
Mean	12.34	20.29	19.98
Median	9.49	12.88	10.74
10 percentile	2.50	3.90	1.92
25 percentile	4.93	7.29	5.35
75 percentile	16.54	22.86	20.85
90 percentile	25.79	43.95	43.56

The polar plot figures, which show the relationship between the wind speed, direction and the $PM_{2.5}$ concentration show that similarly to PM_{10} the periods of highest $PM_{2.5}$ concentration are associated with periods of high wind speed (> 6m/s). At the Mokopane station there is a hotspot of high $PM_{2.5}$ concentration associated with moderate wind speeds (4-6m/s) from the south-west and north-west. This wind direction corresponds to the location of the low income residential areas and associated agricultural areas of Sekgakgapeng and Masodi, respectively.

The trend analysis for $PM_{2.5}$ (Figure 12) shows no significant trends in the $PM_{2.5}$ concentrations at any of the sites. This is in contrast to the PM_{10} concentrations which show a mean decrease at all sites and which is statistically significant at the Lephalale site. This could indicate that the sources of PM_{10} and $PM_{2.5}$ at Waterberg sites are different and therefore different management interventions are needed to address them.

The time variation plots for $PM_{2.5}$ are similar to those of PM_{10}; there is a clear seasonal pattern, with the highest $PM_{2.5}$ concentrations recorded during the winter period. A strong diurnal pattern exists with morning and evening peaks and there is a weekly cycle where an increase in the $PM_{2.5}$ concentrations is observed

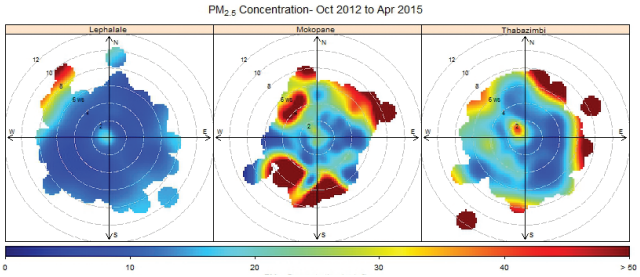

***Figure 8:** Polar Plot of the $PM_{2.5}$ concentration at the Waterberg monitoring stations*

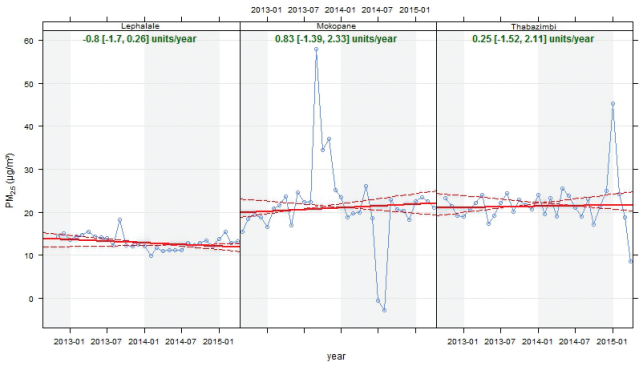

***Figure 9:** Monthly Mean Deseasonalised $PM_{2.5}$ Trend for the period Oct 2012-April 2015. The solid trend line represents the mean slope of the trend, while the dashed trend lines represent the 95% confidence interval of the slope*

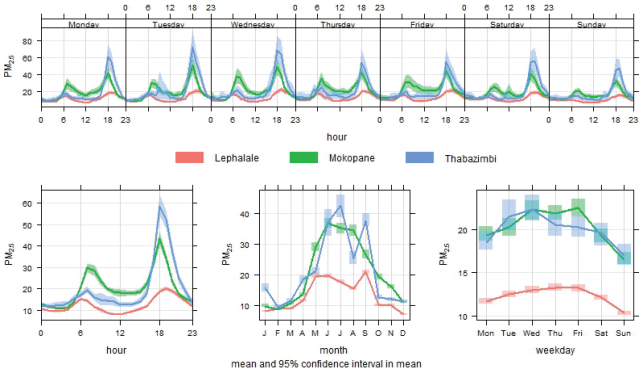

***Figure 10:** $PM_{2.5}$ Time variation plot for the period October 2012 to April 2015*

between Monday and Friday followed by a large decrease over the weekend, with an especially large reduction in the morning peak over the weekends.

Ozone

The mean ozone concentrations recorded over the period ranges between 24.2 ppb (Lephalale) to 28.2 ppb (Mokopane and Thabazimbi) (Table 5).

The periods of high ozone concentration are typically associated with periods of relatively strong winds, specifically from the north westerly sectors for Lephalale and Mokopane. In a study of ambient air quality in the Vaal Triangle high ozone concentrations were observed under similar conditions during the approach of a cold front over the South African interior (Feig

et al. 2014). For all the sites during periods of very low wind (as is typical of night time conditions) the ozone concentrations are very low The periods of high ozone concentration at the Thabazimbi site are associated with winds from the north east and easterly directions.

***Table 5**: Ozone measurement summary*

	Lephalale	Makopane	Thabazimbi
Number of measure-ments	21061	20708	20255
% recovery	94.12%	89.6%	90.5%
Mean	24.27	28.20	28.21
Median	23.52	27.23	27.88
10 percentile	4.81	11.88	7.44
25 percentile	12.65	18.62	16.18
75 percentile	34.07	36.65	38.52
90 percentile	43.57	45.41	48.78

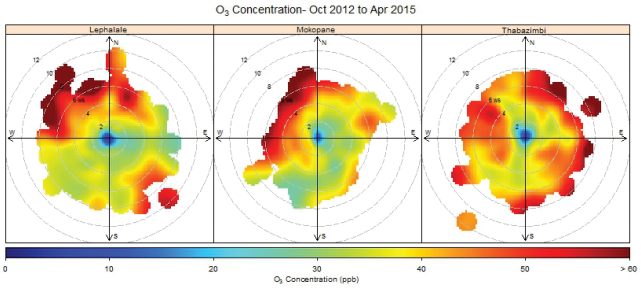

***Figure 11:** Polar Plot of the O_3 concentration at the Waterberg monitoring stations*

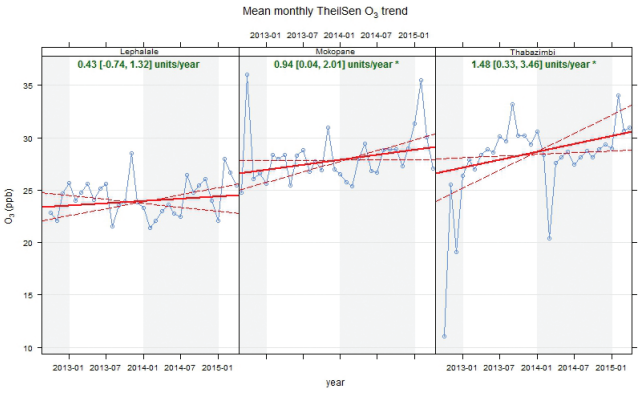

***Figure 12:** Monthly Mean Deseasonalised O_3 Trend for the period Oct 2012-April 2015 the solid trend line represents the mean slope of the trend, while the dashed trend lines represent the 95% confidence interval of the slope*

The trend analysis (Figure 16) indicates that over the monitoring time period there is a statistically significant increase in the monthly ozone concentration (P<0.05) at the Mokopane and Thabazimbi stations. This increase is 0.94ppb/year and 1.48ppb/year for the Mokopane and Thabazimbi station respectively.

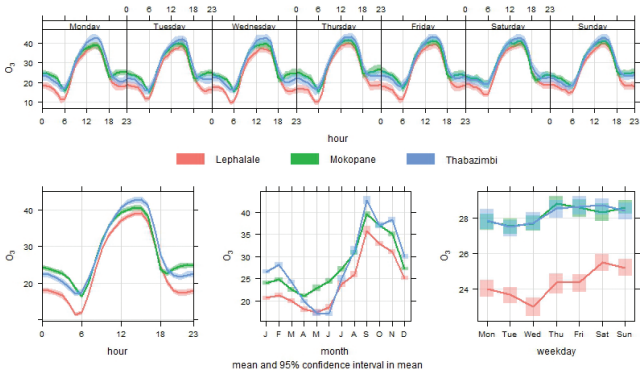

***Figure 13:** O_3 Time variation plot for the period October 2012 to April 2015*

There is strong seasonal trend in the ozone concentrations observed at all the stations, with peaks in the ozone concentrations being observed in the September/October periods, which has been frequently observed and reported (Thompson et al. 2003; Thompson et al. 2011; Thompson et al. 2014; Scholes & Scholes 1998; Zunckel et al. 2004)

Conclusion

This study aims to provide an assessment of the ambient air quality monitoring that has occurred in the Waterberg priority area between October 2012 and April 2015. Data recovery from the three monitoring stations has been good with a valid data capture percentage of greater than 80 % for all the stations.

The recorded SO_2 concentrations are generally low. At the Lephalale station there is a strong source of SO_2 located to the west and north-west of the station that is likely a high level industrial source. The Thabazimbi station shows a distinct peak in SO_2 concentrations on Wednesday mornings.

The PM_{10} and $PM_{2.5}$ concentrations show a strong seasonal pattern with the highest values occurring during the winter months. There has been a statistically significant decrease in the PM_{10} concentrations at Lephalale over the monitoring time period, which is not seen in the $PM_{2.5}$ concentrations. The periods of high PM_{10} concentration are associated with high wind speeds. In addition to the temporal patterns in the PM_{10} and $PM_{2.5}$ concentrations are indicative of local domestic combustion or traffic sources in that there are strong peaks in the early morning and evening, and a strong weekend effect is seen especially with regards to a reduction in the morning peak during on Saturdays and Sundays.

The concentrations of ozone are highest in the spring period, similarly to what has been found in the Vaal Triangle high ozone events may occur during the advance of a frontal system across the country (Feig et al. 2014).

The Waterberg priority area was declared in anticipation of the development of air quality problems associated with the development of the Waterberg coal fields. The initial analysis indicates that the area may already be facing air quality problems, prior to the initiation of the major planned

developments in the area. The continued operation of these ambient air quality monitoring stations will be vital in assessing the pollutant concentrations in the area and monitoring how the pollutant levels change with the implementation of the planned developments. This paper also demonstrates the value of utilizing advanced data analysis methods in order to identify potential pollution sources and to track trends in the ambient air quality over the region.

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