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Editorial

Evidence for health effects of early life exposure to indoor air pollutants: what we know and what can be done

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http://dx.doi.org/10.17159/2410-972X/2017/v27n1a1

The World Health Organization (WHO) recognises that environmental pollution is a major cause of global disease, death and disabilities with a toll greater than that caused by HIV/AIDS, malaria and tuberculosis combined. About 94% of pollution-related deaths occur in low-income and lower middle income countries; for example, childhood pneumonia and diarrhoeal diseases are directly linked to environmental pollution.

Globally, about 40% of the population relies on biomass fuels such as wood, charcoal, crop residues and animal dung for cooking and heating in their daily life (Bonjour et al. 2013). Combustion products of these fuels are a complex mixture of health-damaging pollutants comprising gases and fine particles, containing among others carbon monoxide (CO), suspended fine particulate matter ($PM_{2.5}$), nitrogen oxide, polycyclic aromatic hydrocarbons and volatile organic compounds, as well as toxic metals that are present in fossil fuels and are emitted during burning.

In 2012, more than four million deaths were attributable to household air pollution generated by the use of biomass fuels for cooking and heating, and it has been acknowledged that household air pollution is considered to be a major contributor to the global burden of disease (WHO 2016; Lim et al, 2012).

Thus, the negative impact of air pollutants on the environment and human health alike can be attributed to outdoor and indoor air quality. The negative health impacts of indoor air pollution affect poor populations mostly, who rely primarily on biomass fuels for their day to day living. It is important to note that the indoor environment also reflects the outdoor air quality and pollution. In addition, the populations which are most affected by environmental pollution are vulnerable populations such as pregnant women, their infants, and young children. In terms of exposure to solid fuels, it is well recognised that women and children are most exposed to particulate matter and gases at levels which may be 10 to 100 times above safety standards for ambient air.

It has been shown that exposure during pregnancy to particulate matter, gaseous compounds and inorganic and organic pollutants, even at very low concentrations and irrespective of sources, may have negative impacts on foetal development and birth outcomes, as well as on reproductive health in general. The negative impact of these pollutants becomes more pronounced in populations with low socio-economic status, and compromised dietary and health habits. Recent study performed in Tanzania have shown that prenatal exposure to inhaled particulate matter and carbon monoxide may be associated with foetal thrombosis (Wylie et al. 2017). Another study performed in coastal regions of South Africa have shown that using fossil fuels for cooking increased the levels of arsenic in maternal and cord blood, possibly due to its presence in fuels but also the ability of arsenic to attach to respirable particles present in indoor air (Röllin et al. 2017).

Air pollution health impacts in early life and during childhood development are of major concern worldwide, especially the health impacts due to pollutants present in indoor air as a result of fossil fuel combustion. Epidemiological research has shown that exposures to pollutants in early life are especially hazardous at conception, during pregnancy *in utero*, during the neonatal stage after birth, and in early childhood. One of the most vulnerable life stages is the time between conception and birth, when environmental pollutants exert constant and lasting toxicity on the developing foetus and the mother alike. During this period, rapid growth and organ development takes place. Consequently, not only does the health status of the expecting mother affect this process, but so too a range of external factors, including exposure to pollutants.

Exposure to pollutants in the embryonic, foetal, and early post-natal life stages can result in permanent alterations to organ function. When this happens, acute or chronic diseases may surface at any age, from infancy to old age. For example, exposure to CO in the second month of pregnancy (the period of foetal heart development) may increase the risk of the infant being born with heart defects.

Pre-term births, low birth weight, cognitive and behavioural disorders, and respiratory diseases including asthma, have all been linked to exposure to toxic air pollutants. Additionally, exposure to toxic pollutants may increase the risk of infant deaths at birth or during early infancy, or of infants being born with birth defects. Those who survive may suffer from brain, respiratory and digestive disorders. It has been reported recently that delays in foetal developmental may increase the risk of chronic conditions such as heart disease and diabetes in adulthood.

After birth, in the post-natal and childhood stages, maturation of organs such as brain, lung, and the immune system, continues to the age of six years and beyond, and exposure to specific toxic air pollutants during this period may further reduce lung function, exacerbate asthma, and increase the prevalence of wheeze and allergic rhinitis. In addition, neurodevelopmental disorders linked to exposure to specific indoor air pollutants remain an area of concern.

The scientific data indicate that reliance on fossil fuels should be significantly reduced to prevent the cumulative risks of illness and possible impairments in the affected populations, especially children. The effects of exposure to air pollutants are influenced by individual susceptibility which depends upon factors such as age, developmental stage, nutrition and social support. Indoor air pollutants are potentially more detrimental to children because their lungs are still growing and maturing; younger children breathe more air and require more oxygen than older children or adults; and they spend more time in indoor environments. These susceptibilities are known to be altered by contributing factors such as health, nutritional and socio-economic status.

Emissions from fossil fuels are also major contributors to climate change, resulting in heat stress disease, malnutrition, infectious disease, physical trauma, mental ill-health, and respiratory illness – all having the potential of becoming additional stressors in early life, childhood development and beyond.

Research to date has shown that there is a pressing need for proactive engagement between public health and environmental agencies, at both country and global levels, to drive the process of eliminating and/or controlling sources and generation of toxic air pollutants. Coupled to this process should be the identification and implementation of interventions at various levels (e.g. pollution source, home environment, user behaviour) to reduce indoor air pollution from solid fuels.

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News

ISIAQ 2016: Summer School and Indoor Air Conference in Ghent, Belgium

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In July of 2016, I attended both the 1st International Society of Indoor Air Quality and Climate (ISIAQ) Summer School (2-3 July) and the 14th International Conference on Indoor Air Quality and Climate Change (3-8 July).

The summer school was held prior to the Indoor Air Quality Conference and brought together 34 students from 5 continents. There were seven prominent speakers:

- William Nazaroff, University of California Berkley.
- Andrea Ferro, Clarkson University.
- Andrew Persily, National Institute of Standards and Technology.
- Pawel Wargocki, Technical University of Denmark.
- Brent Stephens, Illinois Institute of Technology.
- Martin Tauble, National Institute of Health and Welfare.
- Ken Parsons, Loughborough University.

Topics such as indoor air quality and exposure, ventilation, microbiology and the built environment, as well as thermal comfort and human perception provided for interesting and informative discussions.

The organising committee not only made sufficient time for learning but also for socialising. A highlight was a field visit to the Flemish Administrative Centre, also known as the '*Virginie Loveling Building*', for a practical demonstration on indoor air quality auditing of a sustainable building. We had plenty of time to explore the beautiful city of Ghent, Belgium and also get to know the other participants and their specific fields of interest were within indoor air. The summer school ended on a high note with the opening ceremony of the IA conference.

The conference itself hosted more than 800 participants from around the world. Themes included fundamental surrounding indoor air; healthy and sustainable buildings; abatement and reduction; emerging issues in indoor air science; smart houses; developing countries; innovative solutions in practice; and standards and codes. Topics were multi-disciplinary in nature and ranged from workshops to interactive poster sessions. It was difficult to choose which session would be attended next!

ISIAQ Summer School 2016: Summer school student from five continents coming together to build knowledge on aspects surrounding indoor air

ISIAQ Indoor Air Conference 2016: Poster presentation given on respirable particulate matter in the indoor environment of low-income settlements on the South African Highveld (Photo credit: Aneka Kļaviņa)

The week spent at the conference gave ample opportunity to network with scientist from across the globe. This opportunity enriched my knowledge surround indoor air by magnitudes, and for that I thank Professor Stuart J. Piketh for sponsoring me in my knowledge gaining endeavours.

Book review
Tomas Foken's book Micrometeorology (Second Edition) 2017

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http://dx.doi.org/10.17159/2410-972X/2017/v27n1a3

This book is a revised edition (second English language Edition, translated by Dr. Carmen Nappo and Prof. Dr. Petra Klein from the third German language edition for the book "Applied Meteorology-Micrometeorological Methods") to one of the essential texts in the field of micrometeorology. Thomas Foken is one of the leading scientists in the field and his work has influenced many of the recent developments, especially related to his work on the effect of landscape heterogeneity. He has been involved in many of the major international flux tower networks such as CARBOEurope where he developed of many of the quality assurance/quality control (QA/QC) processes. His parameterisations, corrections and analyses are included in commonly used flux processing software, *inter alia* EddyPro and EddySoft.

The book covers a comprehensive theory of atmospheric processes in the first three chapters, and the three subsequent chapters (experimental methods, modelling and measurements techniques) are concise and consistent with the theory chapters. Thus, this book is valuable both as a text book for students and the development of teaching material in micrometeorology and can serve as a reference to practitioners in disciplines that require the use of micrometeorology or the incorporation of micrometeorological concepts. While the audience of this book is primarily the eddy co-variance flux measurement community, I believe it will hold great value for air quality practitioners, including those involved in dispersion and atmospheric chemistry modelling, the air pollution measurement community, and regulators who need to understand the atmospheric processes that affect the movement and dispersion of atmospheric pollutants.

The new edition includes an update of the references and the inclusion of new topics relevant to micrometeorological investigations, such as the soil chamber measurements, local climates and land use change.

The book is divided into 8 chapters, including:

General basics: this chapter covers the basic concepts of micrometeorology such as atmospheric scales, processes within the atmospheric boundary layer, the energy balance at the earth's surface and how this drives (the air pollution relevant processes of) turbulence.

Basic equations of atmospheric turbulence: this chapter covers the equations necessary to understand turbulence in the lower atmosphere, including; the equations of motion, turbulence kinetic energy, flux-gradient similarity (including the Monin-Obokov similarity theory and the Bowe-Ratio Similarity), flux-variance similarity, the turbulence spectrum and equations of the atmospheric boundary layer. Although the level of mathematics involved is not really difficult, its presentation requires devoted reading, otherwise, this chapter may be more useful as a refresher to a reader who has completed introductory course related to atmospheric processes.

Specifics of the near-surface turbulence: this chapter assesses the important surface characteristics that affect the turbulence and mixing in the lowest atmospheric levels. This includes; discussion of the surface properties (e.g. the surface roughness, the zero-plane displacement and profiles within plant canopies), the development and characteristics of internal boundary layers, the effect of obstacles on air flow and turbulence; the use and application of footprint models; the impact of high vegetation; the impact of advection, and (of importance to the South African situation) conditions under stable stratification.

Experimental methods for estimating the fluxes of energy and matter: this chapter focuses on the most commonly used methodologies for estimating the fluxes of greenhouse gases water and matter. The methods covered include: the profile method, the eddy covariance method, flux variance relations, accumulation methods, and (of importance to the Air pollution and ecological communities) the wet and dry deposition of nitrogen and sulphur containing compounds.

Modelling of energy and matter exchange: this chapter examines the methods employed for modelling the exchange of matter and energy between the surface and the atmosphere. Techniques covered include: energy balance methods, hydrodynamical multilayer models, use of the resistance approach, boundary layer modelling, modelling in large scale models, large eddy simulations, and methods for area averaging.

Measurement techniques: the chapter on measurement techniques provides essential information for anyone undertaking meteorological measurements and the principals are directly transferable to air quality measurements. The chapter covers the following sections; the principals of data collection (with specific reference to signal sampling, the transfer functions and inertia in the measurement systems), the measurement of essential meteorological parameters, and processes for quality assurance and quality control of meteorological (and other) measured data. The chapter also draws important distinction in flux processing methods which is more suitable for eddy covariance audience. The section includes a detailed comparison of different flux measurement techniques and makes recommendations on the right correction methods based on the site and instruments being used.

Microclimatology: this section examines the importance and mechanisms of small scale climates. This includes; climatological scales, the generation of local climates, microclimate relevant circulations (such as the land-sea and mountain-valley circulations), cold air flows, and the impacts of land use change on local climates.

Applied Meteorology: this chapter focuses on the practical applications of micrometeorology many of which are relevant for the NACA community. Specific applications include; air pollution, sound propagation (noise pollution), wind energy use, and human biometeorology.

Appendix: I found the appendices very useful as they provide a quick reference guide to the correct SI units, important constants and parameters, important functions and equations, parameters required at various types of meteorological stations, and a detailed comparison of eddy covariance software.

Micrometeorology Second Edition by Thomas Foken is published by Springer (Berlin). It is available from the publisher (http://www.springer.com/gp/book/9783642254390) as either an eBook or Hardcover, individual chapters can be bought from the Springer website.

Book review
Patricia Forbes' book Monitoring of Air Pollutants: Sampling, Sample Preparation and Analytical Techniques

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http://dx.doi.org/10.17159/2410-972X/2017/v27n1a4

The Elsevier series, "Comprehensive Analytical Chemistry" has released a volume on monitoring ambient air pollution. This volume, edited by Patricia Forbes, provides information on sampling and measurement techniques for ambient air pollution, including examples of the use of the techniques and instruments in real-world settings.

This is an excellent reference book providing detailed information on a variety of sampling techniques and analytical methods to measure air pollution. While the series is aimed at analytical chemists, the book is also a useful reference for anyone in the field who measures air pollution or who uses monitored air pollution data. As someone who does limited measurements currently, but uses monitoring data very often, this book is a helpful reference to understand the theory behind the measurement technique used, as well as the limitations. This can help to ensure that the data are not used incorrectly!

The book itself is divided into three sections, providing; i) an introduction, ii) techniques on sampling and sample preparation, and iii) analytical methods used to measure ambient air pollution. The chapters cover both established methods, as well as emerging methods.

The sampling techniques discussed in the book include;

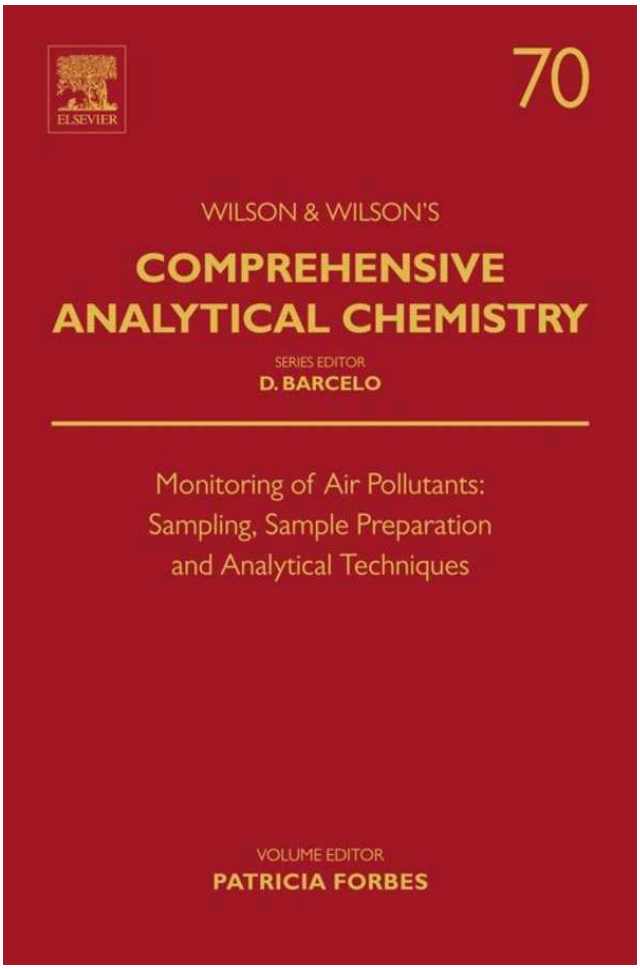
- passive sampling,
- biomonitors,
- whole-air sampling,
- denuders, and
- automated continuous air monitoring.

The analytic methods described are;

- spectroscopic and chromatographic techniques for metals, metalloids and ions,
- chromatographic techniques for organic analytes,
- mass spectrometry and ion mobility spectrometry, and
- microscopic single-particle methods.

A feature that I found to be very useful are the number of case studies (many drawn from African examples) that highlight how these techniques have been used in in practical applications. I find it a great advantage that the African case studies are included as they provide lessons on the application of these techniques to the conditions that scientists working in Africa and the developing world face.

This book is a very helpful reference to researchers who are measuring pollutants in ambient air and want to craft an appropriate monitoring plan. In addition, it is a very valuable resource for all the researchers who use and analyse monitored data, in order to understand the limitations of the data that they use.



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Available for purchase online at www.elsevier.com.

Report review
Air Quality: Missing the wood for the trees by Ivo Vegter published by the South African Institute of Race Relations, September 2016

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http://dx.doi.org/10.17159/2410-972X/2017/v27n1a5

This report of just under 20 pages into South Africa's air quality situation comes out with its conclusion right on the front page as a subtitle: "Indoor pollution is SA's most serious air quality problem". The title, *Air Quality: Missing the wood for the trees*, itself is clearly polemic. Upon reading the title, one wonders exactly who it is that is missing the wood for the trees. The answer becomes apparent in the first line of the introduction section, namely that when examining air quality *media and activists* focus of industrial pollution but loose sight of what the author regards as the real problem, namely indoor air pollution.

Content of the report

The report is a synthesis of existing published material on air pollution in South Africa complemented with case studies derived from interviews with residents of Concordia, on the outskirts of Knysna, in the Western Cape.

After the introduction that contains the main argument in abbreviated form, the report is made up of four more sections.

Section two critically discusses what Vegter believes to be a sensationalist treatment of ambient air quality in South Africa. Vegter is convinced even though the body of evidence is sparse and fragmented, a look at the available facts *exposes the superficial, sensational and piecemeal treatment that environmental lobby groups and much of the media apply to air quality*. He is convinced the there is no national air quality problem but he does acknowledge that hot-spots exist where air quality standards are exceeded, noting that air quality exceedances are common in cities worldwide. The sensationalist coverage of the process where 37 industries applied for postponement of the deadlines for compliance to minimum emission standards is critically assessed. Vegter gives a brief overview of results of the 13 monitoring stations operated by DEA in the three priority areas that was taken up in the 2016 World Health Organization (WHO) Global Urban Ambient Air Pollution Database. In eight out of the 13, the annual standard for PM10 was exceeded (year not given). Vegter then contextualises this with reference to Brazil, China and India where the former two appear to have even higher average concentrations than those found in South Africa.

He develops the argument that indoor air pollution is a greater source of concern making use of a case study with households who use wood for cooking and heating. A key element of Vegter's argument is the notion that indoor exposure is more important than ambient exposure. He support this with a quote from Norman et al.: *Although attention to air pollutant emissions is dominated by outdoor sources, human exposure is a function of the level of pollution in places where people spend most of their time. Human exposure to air pollution is therefore dominated by the indoor environment.*

Section three deals with the effects and consequences of indoor air pollution in comparison to other types of pollution. The first subsection discusses the health effects of indoor air pollution with particular focus on acute lower respiratory infections. With reference to a 2009 article by Brendon Barnes, Vegter asserts than *Indoor air pollution accounts for the deaths of 1,400 South African children per year* although he later states that *…specific studies with large enough sample sizes that link changes ALRI* (in acute lower respiratory tract infections) *incidence with indoor air quality have not been made*.

The second subsection in this section makes use of research by the Medical Research Council's (MRC) Burden of Disease Research Unit to show that, for the year 2000, indoor air pollution was responsible for fewer deaths but more disability-adjusted life years (DALYs) than ambient air pollution. The fact that, according to the MRC's calculation, indoor and outdoor air pollution, even when combined, account for less than 1% of all healthy life-years lost in South Africa is used to argue that a single-minded focus by activist groups on pollution from mines and industry is misplaced since it risks dismissing solutions that have a higher benefit-to-cost ratio and may have significant health benefits. The last subsection deals with the economic consequences of indoor air pollution and emphasises the lack of good data on the subject, but speculates that benefits may be large.

Section four deals with solutions to indoor air quality problems. Vegter briefly discusses electrification, alternative top-down ignition of coal fires, low smoke fuels, improved cookstoves, thermal insulation of houses, LP gas and biogas. Vegter notes the advantages of electrification but also the barriers that limit complete adoption of electricity by all households for all utilities. He briefly describes some of the background relating to the alternative top-down ignition method for coal fires noting the problems inherent in behaviour-change interventions. The macro-scale experiment conducted by the then Department of Minerals and Energy (DME) in Qalabotjha in 1997 is mentioned, noting that low-smoke fuels have potential to improve indoor air quality. Vegter briefly discusses 'improved' cookstoves based on a 1996 study comparing different cookstoves and an open fire. He also mentions the problem of approximately three million uninsulated RDP houses and the benefits that thermal insulation of such structures may have. Vegter notes the obvious benefits that replacing solid fuels with liquefied petroleum gas (LPG) may have. He questions the rationality of the Department of Environmental Affairs' (DEA) suggestion in the *Draft Strategy to Address Air Pollution in Dense Low-Income Settlements* that the uptake of LPG can be increased by regulation of the price of not only LPG but also of LPG cylinders. Vegter notes that although biogas has limited applicability because it requires a fairly large investment and a minimum amount of water and dung, there are some benefits that merit further research and support.

Vegter mentions a series of international examples of interventions to reduce indoor air pollution through improved ventilation, improved stoves, biogas stoves and behaviour change to show that success in reducing indoor air pollution can be achieved.

With reference to a 2006 article by Leiman et al., Vegter introduces the theme of cost-benefit analyses. He emphasizes the point made by Leiman and also by Yvonne Scorgie that interventions focused on household pollution sources result in positive cost-benefit ratios while additional industrial *controls are not yet justifiable in terms of health care benefits as weighed against costs*.

The section concludes with a subsection called *Private sector opportunities and solutions* where Vegter points to the *opportunity for the private sector to make a difference given the slow progress of government programmes and the lack of resources among non-governmental organisations*. Apart from the obvious corporate social responsibility opportunities, he seems to be positive about the business prospects in marketing cleaner energy products to households. He provides examples of such businesses from Kenya, Pakistan and Guatemala. Air quality offsets are discussed at some length (compared to other aspects). He makes reference to Eskom's air quality offset pilot project in Kwazamokuhle. He mentions the opposition to this by environmental groups but emphasizes that the law allows for offsets and that there are clear advantages to this approach.

The document closes with a *Conclusion* section where the main argument is summarized. The argument is this: Media and activists tend to focus on ambient air pollution resulting from industries as a source of concern. They are correct in the case of a few hot-spots but this should be viewed within the context that cities world wide are polluted. Pollution from household sources have a far greater impact than industrial air pollution. Even if indoor and outdoor air pollution are viewed together they contribute less than 1% to the national disease burden. Examples of solutions to pollution from domestic sources do exist but there are still barriers. *An economic analysis shows that cleaning household air is more economical and yields greater social and health benefits than attempts to reduce industrial pollution. Private sector incentives may improve the quality, reach and long-term success of projects to clean the air in people's homes. Offsets could balance the dividends from indoor air pollution improvement projects against the costs of legislated emissions obligations*.

Analysis

The report is a short and not overly nuanced treatment of a complex topic. Vegter does not seem to be very familiar with the field but he does manage to spot a structural problem in the discourse perpetuated by, as he calls it, *media and activists*, especially as far at the resistance to air quality offsets are concerned.

There is one conceptual ambiguity that permeates the whole document: Vegter seems to use the term *indoor air pollution* almost as equivalent to air pollution from domestic sources as if domestic sources do not also lead to ambient air quality problems or pollution from large point sources do not ingress into houses. For example, with reference to the DEA's Environmental Offsets Discussion Document he notes that *…legal provisions that would permit companies to reduce their cost of regulatory compliance by funding innovative indoor air quality programmes could work, but only if these offset programmes are transparent and subject to independent oversight to limit corruption*. This ambiguity is present throughout. It seems as if the distinction between the place where an activity is located, the place where an emission occurs and the place where a person is exposed passes him by. The distinction is important however. The operation of a cast iron coal stove, of which there are still some hundreds of thousands in use in the townships on the highveld, can serve as an example: the activity of using the stove takes place indoors, a small part of the emission is also emitted into the indoor environment during the ignition process and through cracks in the stove or chimney. The larger proportion of the pollutants are, however, emitted into the ambient environment through the chimney. The people who are exposed to the indoor emissions are the household who performs the activity themselves. This exposure also takes place indoors. The people exposed to the emissions into the ambient environment may be the same household, the neighbours and the people in the same town. This exposure may occur outdoors when people are outside but also indoors as ingress of pollutants into houses (and possibly also accumulation) takes place. Following the principle of charity I read "indoor air pollution" in the text to mean all air pollution resulting from domestic activities.

The part of the argument that builds up to the assertion that there is no national air quality problem is somewhat contradictory. It starts with the acknowledgement that *Reliable and comprehensive statistics about air pollution, whether indoor or outdoor, are hard to find. Surveys and estimates are often incomplete, outdated, based on sparse information and* *sometimes inconsistent with each other* but then insists that a comprehensive look at the information yields exposes the *superficial, sensational and piecemeal* treatment of air quality by environmental lobby groups and much of the media. The irony is that a comprehensive overview of incomplete data is still incomplete.

This subsection dealing with the question of whether there is a national air quality problem is basically an *argumentum ad auctoritatem*. Vegter follows the 2005 Country report to the United Nations Conference on Sustainable Development (UNCSD) by the DEA where it is claimed that there is no national air quality problem but air quality is poor in certain hot-spots without any critical reflection. He appears to find comfort in the fact that the 2010 report to the UNCSD does not mention air quality at all. He chastises the media and environmental groups for neglecting to mention that almost all cities in low- or medium- income countries have air quality problems. The definition of what constitutes an air quality problem appears to differ between Vegter and his ideological opponents. Vegter seems to think that as long as we don't have more problems than anyone else, we are fine. The environmental groups compared air quality in Johannesburg to the WHO guidelines. There is a clear difference in outlook.

I think Vegter is correct to find it disappointing that Earthlife Africa and groundWorks did not contextualise the air quality findings within the international context, but I find his low levels of ambition disappointing. It is fully possible to aspire to high standards and have a realistic understanding of how difficult it will be to reach those standards. There are many fields of research and practice that are difficult and acknowledged as such, such as alleviating mass poverty, curing cancer or rehabilitating heroin addicts. Practitioners and researchers in these fields start by acknowledging that the field of practice is difficult and the research questions are complex. Air quality is one of these fields.

The most disappointing section of the report is the section on *Solutions to indoor air quality problems*. His treatment of electrification and biogas use are a bit of an exception. He shows how electrification does lead to a reduction in exposure to pollutants and shortly explains the barriers to full electrification. The conclusion is that full electrification would have worked but is unrealistic and that the recommendation in the DEA strategy document is of precious little help. The *DEA's recent draft strategy for addressing air pollution in poor communities says little about free basic electricity apart from stating that "government will explore new ways of providing electricity subsidies"*. In the case of biogas he at least acknowledges the small potential impact.

In the rest of the section it becomes apparent that Vegter has superficial knowledge of the subject matter. This is especially clear in the lack of reference to the context onto which each of the intervention candidates are orientated as well as his lack of vision as to the relationship between intervention candidates. He does little else than name and shortly describe a list of intervention candidates in differing phases of development, with different socio-economic and spatial areas of applicability and with markedly different expected impact as far as potential impact and likelihood of success is concerned. Nowhere does he even attempt to say anything about what it will take to implement any of the interventions and what imaginable effects it may have. After this section one may conclude that we do not have any workable solutions in hand. He may not necessarily be so wrong on this point (although he missed the results of two major initiatives involving thermal insulation(see Langerman et al. 2015 for the work by Eskom and https://tinyurl.com/y7zkgfg3 for that by Sasol), one of which he refers to in the future tense when it has in fact been implemented). The inevitable conclusion that air quality interventions are difficult undermines the confidence he expresses in the last section about the possibility of *developing business models that provide profitable opportunities for large companies and small entrepreneurs to sell solutions that work and are affordable to the urban and rural poor*.

After all, convincing people to buy such solutions is the challenge of all business, whether the target market is rich or poor.

He refers to the DEAs, *Draft Strategy to Address Air Pollution in Dense Low-Income Settlements* from 2016 although he misses the significance of subsection 2.7 where sources of air pollution in dense, low-income settlements other than domestic solid fuel use are listed.

Sources

The report makes use of a limited number of sources and misses some important ones. Vegter's argument hinges on a few key assertions. In the paragraphs that follow I will look into the sources of these assertions and make a few critical remarks.

The assertion that the burden of disease from indoor air pollution is larger than that from ambient air pollution plays an important part in Vegter's argument. The source of the assertions on the burden of disease of ambient and indoor air pollution are two articles that resulted from the MRC's *Comparative Risk Assessment* (Norman, Cairncross, et al. 2007; Norman, Barnes, et al. 2007) as well as the summary report of that project. In these articles the burden of disease of both urban and indoor air pollution is estimated for the year 2000.

Two sources are used for assertion that cost-benefit ratios for interventions aimed at household pollution sources are higher than that for industrial emission controls namely an article by Leiman et al. (2007) and Yvonne Scorgie's doctoral dissertation. These two sources are in remarkable agreement. Vegter refers to these as if they are two sources: "*Ms Scorgie's thesis also concludes that ...*" but in fact they both derive from the same source, namely the FRIDGE report from 2004 (Bentley West Management Consultants and Airshed Planning Professionals 2004b, 2004a). Interestingly enough, the FRIDGE report was also the source of the exposure estimate used for Randburg, Rustenburg, the Vaal Triangle and Kempton Park in the MRC study on urban air pollution referred to earlier.

Vegter missed a few important sources in the literature. He seems oblivious of the existence of the Clean Air Journal and would undoubtedly have benefitted from its online archive going back to 1971. He could have benefitted from reading the report on *Air pollution in dense, low-income communities in South Africa* by Friedl et al. (2008), if only for the bibliography that is longer that Vegter's entire report.

Vegter also seemed to miss the significance of the project by Sasol in Kwadela (see Sasol Secunda's Offset Implementation Plan page 6 onwards at https://tinyurl.com/y7zkgfg3), Mpumalanga where about 500 RDP houses where retrofitted with thermal insulation. Vegter does refer to the work done by Eskom in Kwazamokuhle but does not seem to grasp its content.

In his treatment of the alternative top-down ignition technique for coal fires, Vegter only refers to the *Basa njengo Magogo* implementation by the (then) DME and not the initiatives by Sasol or by the Nova Institute that was more sophisticated in implementation and monitoring as well as larger in impact than that of the DME (see https://mer.markit.com/br-reg/public/index.jsp?name=Nova%20Institute&entity=project&entity_domain=Markit,GoldStandard).

Conclusion

When interpreted charitably, I think Vegter is correct: Generally speaking, pollution sources close to poor people, often from dirty fuels used by necessity and not by choice, have a greater impact than emissions from large industrial point sources and therefore should be the focus of interventions. Air quality offsets do indeed provide a mechanism where the regulation of industry can be used to re-focus environmental improvements where they are needed most. The in-principle opposition to air quality offsets is indeed irrational and certain sections of the media and environmental pressure groups needed to be berated.

To my mind there is a need in South Africa to build deeper understanding of air quality issues among all stakeholders, even if it is only to foster better quality disagreement. Vegter makes a contribution to this discussion. However, the chances that after reading his report, the likes of Earthlife Africa and groundWorks will repent and rejoice at the discreditation of their erstwhile selves (to quote John Milbank's review of a book by David Bentley Hart), is slim indeed. This is partly because we live in a day and age where, in public discourse, the semantic accent from talking about something to speaking about of who is allowed to say something, is the rule rather than the exception. It is a pity therefore, that these groups had to be chastised (justifiably so) by an elephant-culling enthusiast[1] with a propensity for climate change scepticism[2] and a blindness in the economic right eye.

The report once again emphasised how limited our understanding of the extent and impact of air pollution in South Africa is. Air quality monitoring stations are limited to a few areas but there are clear indications that the problem is larger than the monitored areas. The work by the MRC team on the burden of disease related to indoor and ambient air pollution refers to the year 2000.

How do we get there from here

Reading through Vegter's report I think of two things, the one is about knowledge and the other is about action. Vegter didn't do a particularly good job of collecting and synthesising authoritative sources. In fairness, that may not have been his purpose. He seems to want to make an argument against his ideological opponents as represented by certain environmental groups. However, as I read through this, I think that we need an update of the FRIDGE report, the DANIDA report[3] and the burden of disease studies, only this time more suited to the 21st century through incorporating emerging paradigms such as reproducible analysis and citizen science - maybe even for all of it to take shape on GitHub[4], complete with forks for alternative approaches.

I had an informal discussion about the idea of citizen science with Dr Gerrit Kornelius at the National Association for Clean Air (NACA) conference last year. His reaction to my enthusiasm for the application of the concept of citizen science to air pollution in South Africa was that such an undertaking is a waste of time because we already know enough about the problem, we now need to act upon what we know instead of getting bogged down in more research. I have great respect for Gerrit's opinion and have often thought about what he said during that conversation since then. He may have articulated himself provocatively, but he is correct. Our knowledge of the problem is far ahead of our implementation of solutions. Following this logic, should one just ignore the environmental naysayers and proceed with the implementation of air quality offsets? As the saying goes: *Those who say it cannot be done should get out of the way of those who are doing it.*

The choice between knowledge and action is not a binary one. One needs knowledge in order to do something. Those who are *doing it*, may not understand exactly *what* they are doing. It furthermore remains important to create a broad social consensus, not only to avoid wasting time and resources on mudslinging and senseless court battles but also to mobilise the energy of all stakeholders. The weakest part of Vegter's report, to my mind, is the portion on potential interventions for, as he calls it, indoor air pollution. This subsection is so weak because it lacks context and quantification. He uses the DEA's *Draft Strategy to Address Air Pollution in Dense Low-Income*

[1] See https://tinyurl.com/yd4egh6p and also https://tinyurl.com/ycnzyl2z

[2] See for example https://tinyurl.com/y7awajhw and also https://tinyurl.com/ycaldwsb

[3] Download at https://tinyurl.com/yaqxxru2

[4] https://github.com/about

Settlements as an important source, and the DEA strategy is very weak on nuanced implementation ideas. This is one area where knowledge is especially sparse, exactly because of too little action. After all, knowledge about implementing interventions is only gained by mindful implementation. The recent projects undertaken by Sasol and Eskom show how air quality offsets gave impetus to both research and action.

It was stricter regulation of industries that set the implementation of air quality offsets in motion. When compliance options are flexible because offsetting offers alternative ways to achieve the environmental impacts envisioned by the regulations, more ambitious environmental regulations can be introduced because there will be possible avenues for compliance. The irony is that, judging by his other writings, Vegter will not necessarily like the idea of stricter regulation of businesses and that the environmentalists totally missed this point.

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Commentary
Challenging the air quality discourse – people create pollution not technology

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The London Smog of 1952 and subsequent health effects brought about a public outcry which triggered the generation and implementation of the UK's Clean Air Act of 1956. This act and subsequent updates has been credited with ending the 'pea-souper' conditions synonymous with industrial and domestic coal burning. In recent years in the UK, the emergence of major smog events in urban areas due to road transport emissions, the growing volume of epidemiological evidence on the health effects of air pollution, the threat of fines by the European Commission towards Member states and the high profile court cases taken forward by ClientEarth against HM Government[1]has once again raise the media and political profile of air pollution but the same public outcry that was evident after the London Smog has not been seen. This story is replicated around the world, where major air pollution incidents are not (yet) resulting in wide scale social action – and consequent political changes – to our approach to tackling air pollution.

It could be argued that the lack of civic engagement with the air quality challenge to date lies in the way in which air quality management processes are undertaken and subsequently communicated - '*people*' are absent in the models and scenarios used to estimate and predict air pollution concentrations. The modelling of emissions sources, not the human activities that result in them, leads to a bias in policy that focuses on mitigating emissions through technological change rather than through changing individual and societal behaviour. In turn, this leads to a consequent reliance on technological innovation not social innovation. Traditional source apportionment approaches have previously considered the '*technology*' that has been responsible for creating the emissions (e.g. cars, HGV, combustion plant, etc.) but the 2015 Volkswagen diesel emissions scandal and subsequent debate on real-world versus test cycle emissions brought to the fore that overreliance on technology alone would not solve our pollution problems. We need citizen engagement. We need to bring citizen's daily practices, activities and behaviours in this debate We need to apportion pollution in a way that make it easier for citizens to make connections between their day to day activities and the generation of pollution e.g. apportioning pollution by categories such as travelling to work, taking children to school, leisure time, commuting etc. We need to embrace new and innovative ways of communicating this challenge to a range of audiences. A new European Horizon 2020 funded project, ClairCity (www.claircity.eu), is aiming to achieve this by systemically changing the way we think about and discuss air pollution.

Cities currently account for only 1% of the earth's surface but half of the world's population, 67% of global primary energy demand and 71% of global energy-related CO_2[2]. In 2012 the WHO calculated that there were seven million premature deaths – one in eight global deaths – annually due to air pollution[3]. Air pollution from EU industry alone was estimated to cost society €59-€189 billion in 2012[4]. These impacts cannot be sustained. However, future projections indicate that 70% of the global population in 2050 will be living in urban areas[5] while cities, industry and commercial activities will require the majority of the forecasted 40% increase in world energy demand in 2020. The complex links, both direct and indirect, between people's day-to-day activities and the collective demands that city populations put on local and global environments, particularly through poor air quality and increased carbon emissions, illustrates

[1] http://www.cleanairjournal.org.za/download/caj_vol26_no2_2016_p02.pdf
[2] International Energy Agency (2008), World Energy Outlook, OECD/IEA2008
[3] http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/
[4] EEA (2014), Cost of Air Pollution from European Industrial Facilities 2008-2012, Technical Report, No20/2014
[5] United Nations, 2014, World Population Prospects: The 2012 Revision, Methodology of the United Nations Population estimates and Projection, ESA/P/WP.235

how the scope of the challenge extends beyond city geopolitical boundaries and reflects the need for long-term pathways to a low carbon, clean air, and healthy future.

Air pollution and carbon emissions are largely a consequence of society's use of energy whether it is for home heating and cooking, personal mobility, employment, industrial production etc. However, energy is not used for its own sake but as part of accomplishing social practices at home, at work and in moving around. Therefore, it can be argued that energy, and by direct association pollution, is an outcome of the social, infrastructural and institutional ordering of what people do. In turn, our lives in future cities will be unlike today's as social and technological innovation continues. Therefore, to truly understand how to mitigate air pollution and reduce carbon in our cities, we need to ask what our cities use energy for and understand how end-uses of energy are changing.

Two decades of established emissions inventories and evolving modelling practices across the EU have only taken air quality management and carbon reduction strategies so far. It can be argued that this is because the policy and methodologies used have, for a number of reasons, led us towards attempts to reduce emissions predominantly through technical measures, and away from changing the way our societies and cities operate and function. Current practices also tend to target the manifestations of problems rather than the cause, for example, by focussing on air pollution hotspots (where), and on transport (what) rather than the behaviour and activities (who and why) that generate transport demand. Additionally, existing approaches to air quality and carbon management are designed to project forward from our current city baselines to achieve reductions in future years. This results in our cities developing into '*what we end up with*' rather than '*what we want*'. To address this issue, air quality and carbon management must put people at the heart of the debate and work with city citizens to create a collective vision of a future desirable city in order to work out what is necessary to do to achieve '*what we want*'.

The air quality discourse and management practices needs to go beyond the traditional '*where and what*' approach to provide a new perspective and a new geography of pollution based instead on '*who and why*' which considers citizens daily activities, behaviour and practices which will clearly allow the connection to be made between pollution and behaviour, and link these to the various practices that constitute everyday life within our cities. In other words, air pollution and carbon management are no longer to be addressed as separate and rather technical policy topics, but to be regarded as part of wider concerns of city inhabitants about their quality of life and healthy futures. In the ClairCity project, this is achieved by creating new platforms to stimulate discussion and engage citizens in a democratic debate about how their cities develop in a manner that protects the local and global environments and puts their health and well-being at the heart of policymaking. Incorporating social research methods, citizen engagement through workshops, an online game, schools' projects and events reaching out into communities, which is underpinned by innovative data analysis, modelling, and policy packages, we are creating a scientifically robust yet flexible methodological framework which is being tested in six European cities but could be adapted and adopted by any global city. By putting citizens and their behaviour at the heart of the debate, we will raise awareness of the consequences of their daily actions on air quality and carbon emissions and the health outcomes, giving citizens ownership of the problem and also the solutions. This, in our view, is key to improved air quality city policies in the future as policies to date have failed to successfully engage citizens because, unlike technological solutions, people and their behaviour are not obviously present in the way that air quality and carbon issues are managed and communicated.

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Company Profile

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Originally formed in 1976, SI Analytics provides air monitoring solutions to industry, government and research organisations. Our analytical instrumentation offers continuous measurement of both surrounding air pollution and chimney emissions.

We design, manufacture, supply, install, commission, train and provide after sales service for either individual monitors, or integrated systems in southern Africa.

SI Analytics is currently a B-BBEE level 2 contributor.

Being a founding member of Europa Environmental gives us the expertise to supply and support advanced environmental monitoring technology.

Our aim is to bring you the world's best instrumentation, spare parts, service, technical support and training - at the most affordable pricing - to meet your environmental monitoring needs.

Services

Due to government regulatory requirements, our clients are under increasing pressure to collect emissions data. This is not part of their core business - their expertise lies in manufacturing the products they sell. Our expertise lies in assisting them to manage their data and compliance issues.

We offer a wide range of services such as ambient air quality and continuous emissions monitoring which include:

- Environmental monitoring
- Certified USEPA, European EN and UK MCerts equipment sales
- Data management and reporting
- Service and maintenance contracts
- Equipment rentals
- Indoor air quality assessments
- Short courses (e.g. Operator monitoring assessment training).

Products

Stand alone products, integrated systems, spare parts, local factory repair, and on-site maintenance are all part of what SI Analytics has to offer, thus providing tailor-made solutions to client applications.

Instrumentation from the most popular products includes:

Ecotech:	manufactures a range of ambient air quality instruments.
Grimm:	mobile and stationary ambient dust monitors.
Ecochem:	extractive high sensitivity gas analyser systems.
Procal Analytics:	in-situ continuous stack gas analysers.
Chromatotec:	chlorine, hydrocarbon and sulphur speciation analysers.

Clients

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SI Analytics has successfully installed and maintained various analysers and systems for a variety of clients such as:

AEL Mining Services, ArcelorMittal, Cape Town, City of Tshwane, Lonmin, Wasteman, Xstrata, East London IDZ, Ekurhuleni, Enviroserv, Environmental Affairs, Sasol, Vale, uMhlathuze, Eskom, Foskor, Johannesburg City Parks, Impala Platinum, Transnet, Zimplats

We also provide data management and monthly reporting services for clients throughout South Africa, Botswana, Mozambique, Nigeria, Zambia and Zimbabwe, amongst others.

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Estimating measurement uncertainty for particulate emissions from stationary sources

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Abstract

The estimation of measurement uncertainty with regards to hazardous air pollution emissions from stationary sources is currently the most uncertain element associated with respect to obtaining relevant, valid particulate matter (PM) emission data in South Africa. This project is aimed at developing an appropriate method to evaluate the uncertainty associated with PM measurements conducted for stationary source emissions in the South African context. A series of In-Stack measurements were taken in accordance with recognized international methodology (ISO 9096:1992 and 2003) on two different industrial processes, representing a compliant and non-compliant scenario. A comparison between the two scenarios was made in an attempt to establish what components of the sampling technique have the greatest error.

The overarching goal of this project was to establish an estimate of the cumulative uncertainty on the final emission values obtained, inclusive of both analytical, field sampling and process related variables that may result in a cumulative error associated with quantifying stationary source PM emission values.

The results of the study found that the estimated combined expanded uncertainty for both sets of data was calculated to be between 62 – 72%. Upon closer analysis of the data it was ascertained that the data obtained were inadequate and the calculation of the uncertainty of the results both with the compliant and non-compliant sampling campaigns revealed that the variability of the results was too great for both scenarios to make any statistically valid observations or conclusions about the data.

In lieu of this the author has developed an alternative tool (a sampling suitability matrix) for assessing the quality and reliability of reported emission figures. It is expected to add significant value to the interpretation of the quality and reliability of the final emission results reported. The intention of this tool is to be incorporated as supplementary information into all emission reports in future. This will enable the plant operator and regulator to assess the quality of reported data and final emission results, thus assisting in establishing whether the plant is in compliance with their Air Emission License (AEL) requirements or not.

Keywords

uncertainty, particulate emissions, stationary sources, gum

Introduction

In 2010, emission standards under the National Environmental Management - Air Quality Act of 2004 (Act 39:2004 or AQA) were promulgated and included priority pollutants identified by the Department of Environmental Affairs (DEA) as having, or may have, a significant detrimental effect on the environment, including health, social conditions, economic conditions, ecological conditions or cultural heritage. Particulate matter was identified as one of the main priority pollutants that may cause harm as particulate matter emissions are regulated in almost every category for listed activities under section 21 of the Act.

The uncertainty of these measurements is difficult to quantify due to the physical nature of particles which may affect their behavior in an off-gas stream. To compensate for the inhomogeneous nature of particulate concentration in the gas stream, the samples are extracted isokinetically from the gas stream utilizing recognized, validated methods (USEPA Methods 5 and 17 and ISO 9096:1992/2003.

Good quality data are essential in the decision-making process for plant operators and regulatory authorities alike. Decisions made on questionable data can lead to costly mistakes from upgrading plant off-gas cleaning systems unnecessarily, to not taking action where necessary as a result of questionable data. The air quality monitoring field is still in its relative infancy in South Africa. The implementation of the new air quality legislation is an ongoing process and is not without its teething problems. This project aims to coincide with the demands of the new legislation to ensure data quality and reliability of reported results. The implementation of a standardized methodology to assess PM monitoring data quality is the ultimate goal of this project.

Main objectives of the study

The main objective of the project is to establish the validity of source emission data (particulate matter emissions) obtained in South Africa. This was achieved by employing the general approach or framework to calculate uncertainty as set out in the "Guide to the Expression of Uncertainty in Measurement" (ISO GUM1995), in which individual uncertainty sources are identified, quantified and combined to provide the measurement uncertainty. This philosophy has been adopted as the underpinning approach within the European and International Standardization bodies and will be used in standardized measurement methods in the future (Robinson 2004).

For the purposes of this study the ISO 9096:1992 and 2003 methods will be utilized for the measurement campaigns. These methods have been chosen due to the fact that the ISO 9096 method was utilized by Levego for the sampling to produce the data sets that will subsequently be utilized in this study. The abovementioned methods are deemed as equivalent methods by the international measurement community and utilizing either method should produce a similar result (environment agency technical guidance note M2:2011 version 8.1).

An attempt is made to estimate the uncertainty of the final emission results and to quantify the effects of not adhering to the requirements of the ISO 9096 methods.

Literature review and research hypothesis

Overview

In reviewing stack emission monitoring surveys conducted in the past, it has been suggested that the greatest components of error are those that are out of control of the sampling specialist. The "International Organization for Standardization ISO 9096 (1992)" method was utilized for conducting the particulate matter measurements for the study, which includes stationary source emissions – the determination of concentration and mass flow rate of particulate material in gas-carrying ducts – manual gravimetric method. According to the method, the following parameters are deemed to be out of the control of the sampling specialist: plant operating conditions, environmental conditions, and the non-compliance of the sampling location to the minimum requirements as set out in ISO 9096:1992 and 2003.

A critical element of a quality system is to ensure that the systems of calibration and measurement are traceable to national standards of measurement and that confidence can be placed in the quality of measurements carried out at all steps in the traceability chain (Clarke et al 1998). Validation is necessary to demonstrate the instrument response over the full working range of the parameter being measured. The methodology utilized in this study is an internationally validated method and therefore the traceability of the method has been determined

If all the minimum components of the standard are complied with then the final reported emission results would be guaranteed to be within + 10 % of the reported value (ISO 9096:1992 and 2003). The problem arises when the minimum requirements are not adhered to. In South Africa, most existing industrial plants have been in operation for decades and as a result have been built without due consideration for complying with the minimum current environmental standards. This poses a problem, especially with regards to obtaining a suitably compliant sampling location.

In contrast to the measurement of gaseous emissions which can be routinely undertaken with an accuracy of a few percent, the measurement of particulate emissions is far more difficult. This arises primarily from the non-uniform distribution of particle concentration within the duct or chimney coupled with the non-uniformity of the gas velocity/off gas flow (Hawksley et al 1977). The above scenarios may occur due to several factors such as bends, dampers etc. in the off-gas ducting. The basic requirement of all extractive sampling techniques is that a sample of the gas taken into the measurement system should be representative of the bulk of the gas stream in the flue. For these reasons, very precise guidelines for particle sampling are required and these are given in the various standard sampling methods utilized (ISO9096:1992/2003 and USEPA 5/17). One can conclude then from the abovementioned properties of particles that firstly the choice of sampling position is vital, and secondly that multipoint sampling should be utilized in almost all applications (Hawksley et al 1977). In practice the adherence to the minimum requirements for a sampling location is said to be the most commonly non-compliant parameter (Hawksley et al 1977).

The reason for the above assumption (non-compliance of the sampling location), is that the laboratory analysis of the samples obtained are done under controlled laboratory conditions to ensure minimal external interference with the sample. The sampling equipment utilized can be adequately controlled by the sampling specialist and all the components of the sampling train can be verified and calibrated where necessary. For these reasons, process type, variability and continually changing environmental conditions have the greatest effect on the final measurement result obtained as these factors are outside of the control of the test technician and are part of the random set of uncertainties that are difficult to quantify and account for (Environment Agency Technical guidance note M2 1993).

From the assumptions mentioned above, several scientific questions can be asked;

- Does the non-compliance of the sampling location and process operating conditions have the greatest influence on the sampling results?
- Can the uncertainty of the measured emissions be determined statistically?
- Can a suitable method of evaluating the acceptability or quality of final emissions data be developed?

In an attempt to answer these questions, two sampling campaigns have been conducted (refer to data and methodology on page 4 for details of sampling campaigns). The first sampling campaign was conducted with all the minimum requirements of the standard) being met. The second sampling campaign was conducted where the minimum requirements for the sampling location and process operations did not adhere to the minimum requirements of the standard. The subsequent comparison and analyses of the data sets obtained from a fully compliant (Source A) and non-compliant (Source B) stack emission campaign will endeavor to answer the abovementioned questions. Once these findings have been established, an attempt is made to use statistical methods to estimate the uncertainty of the measurement when faced with a non-compliant stack.

Whether the estimation of the overall uncertainty is feasible will be determined once the data are evaluated. If it is found that it is not feasible to obtain an estimate of the uncertainty pertaining to the non-compliant measurement scenario, this study will provide the impetus to inform industry of the potential dire consequences of not spending money on projects to ensure that the sampling locations and plant operations are satisfactory for obtaining good quality emissions data.

The trend by many industries at present is to save costs by doing the bare minimum to comply with the relevant standards. As South Africa, which is classified as a developing nation, tends to follow developed country trends, it is safe to say that industry will have to start taking environmental issues seriously and spend money to ensure good quality data. Best practice in developed nations is easier to obtain as they tend to have well established standards and norms, whilst in South Africa one generally has to look abroad for guidance. This situation, although cost effective, is not always appropriate as the standard methods and norms adopted in a developed country may not be entirely relevant or suitable for application in a developing country such as South Africa.

Key findings of Dutch validation study (1999)

According to the findings of the study, the results were disappointing as the reproducibility of the Dutch field study were deemed to be less than satisfactory (ISO 9096:1992 p39). During subsequent meetings with the project support committee and members of the quality committee it was established that the performance characteristics of the Netherlands Standardization Institute (NEN)-ISO 9096:1992 were related to the characteristic properties of the waste gases. This conclusion is based mainly on the discrepancies in the results of repeatability as determined at the three sources. Two of the three sources showed a repeatability of approximately 12-14% (RSD), while the third source had a significantly higher repeatability value, representing poor repeatability, the results also produced disappointing reproducibility. A great difference between the first two and the third source was attributed to the high water vapour content. Moreover, there may be differences in physical composition of the dust in the waste gases. The conclusion, based on the matrix discrepancies in the waste gases, is that evidently a distinction is to be made between 'simple' and 'difficult' sources. It would appear that 'difficult' sources place too high a demand on the measuring method (ISO9096:1992 pg. 39).

On the project support committee's recommendation and after approval thereof by the quality committee, the Nederlanse Onderneming voor Energie en Milieu (NOVEM) / (Netherlands agency for Energy and the Environment) commissioned the performance of supplementary dust measurements on an emission simulation plant as installed at the Hessische Landesanstalt für Umwelt (HLfU) in Kassel, Germany. The purpose thereof was to demonstrate the reproducibility and correctness of measurements for 'simple' sources, so that the result may serve as a basis for the problems experienced with 'difficult' sources. At this plant, not only the reproducibility of the measuring method was determined but also its trueness, as well as the ability of the participating Dutch measuring institutes. The reproducibility was determined at two concentration levels (approximately 10 and 20 mg/m^3). Based on measurements at this plant, a reproducibility of 4.5mg/m^3 (44%) was determined at the concentration level of 10mg/m^3"

A similar order of magnitude was determined at the 20 mg/m^3 concentration level. When taking these Dutch findings into consideration in the context of this study, the conclusion is that the errors and uncertainties with regards to spatial and temporal variations are too great to allow much value to be derived from an in-depth statistical analysis of the results obtained, other than to confirm that there are large uncertainties contained in trying to reproduce results utilizing this method on various plants – be they compliant or non-compliant. Therefore, the imperative to utilize a qualitative approach to complement the emission result is vital in determining the quality of the results obtained, and ultimately the decisions made.

Data and methodology

Overview

The source emission data utilized in this study were obtained from two stack sampling campaigns conducted for the determination of concentration and mass flow rate of particulate matter. The surveys were undertaken by a leading South African source monitoring organization.

The first sampling campaign involved conducting twelve (12) one (1) hour isokinetic stack samples over two days for particulate matter from a large industrial boiler installation, typical of a coal fired power plant found in South Africa (Source A). These data are representative of the best-case scenario where the results represent a stack that complies with all the minimum requirements as set out in ISO 9096:1992 and 2003.

The second sampling campaign involved conducting three (3) one (1) hour isokinetic stack samples over an eight hour shift from a cement kiln installed on a typical cement manufacturing plant (Source B). These data are representative of the worst-case scenario where the results represent a stack that does not adhere to all the minimum requirements as set out in ISO 9096:1992 and 2003. The requirements not adhered to are the requirements specifically related to the suitability of the sampling location.

The comparison of the flow profile data sets for both surveys is included as this has been determined as the most appropriate way to assess the suitability of the sampling location, as an uneven and unstable flow profile is assumed to have the largest single effect on the uncertainty of the final reported results.

Process information

Many sampling campaigns achieve unrepresentative results as the sampling period chosen does not accurately represent the process emission. It is important to note that many sampling techniques have been developed for relatively steady stack emissions, such as power stations, but in some sources it is not unusual to have a 100 fold difference in reported emissions over relatively short time periods from 10days to relatively long time periods of up to 10 months. It is important to obtain as much information as possible about the process before commencing any sampling campaign. However, in practice, little data may be available concerning the process as a result of intellectual property and patent rights resulting in limited information being made available to third parties, such as the test house.

Summary of the sampling method

A representative gas sample is withdrawn from the source. The degree to which this sample represents the total flow depends on the:

- Homogeneity of the gas velocity within the sampling plane (stable, uniform flow within the enclosed flue system is required). The gas flow in off-gas ducts are such that laminar flow is rarely, if at all, achieved (Hawksley et al 1977).
- A sufficient number of sampling points in the sampling plane which would depend on the size of the duct or stack (a larger sampling plane requiring more sampling points).
- The isokinetic withdrawal of the sample will also have a significant effect on the degree to which the sample is representative of the total flow in the gas stream (Hawksley et al 1977).

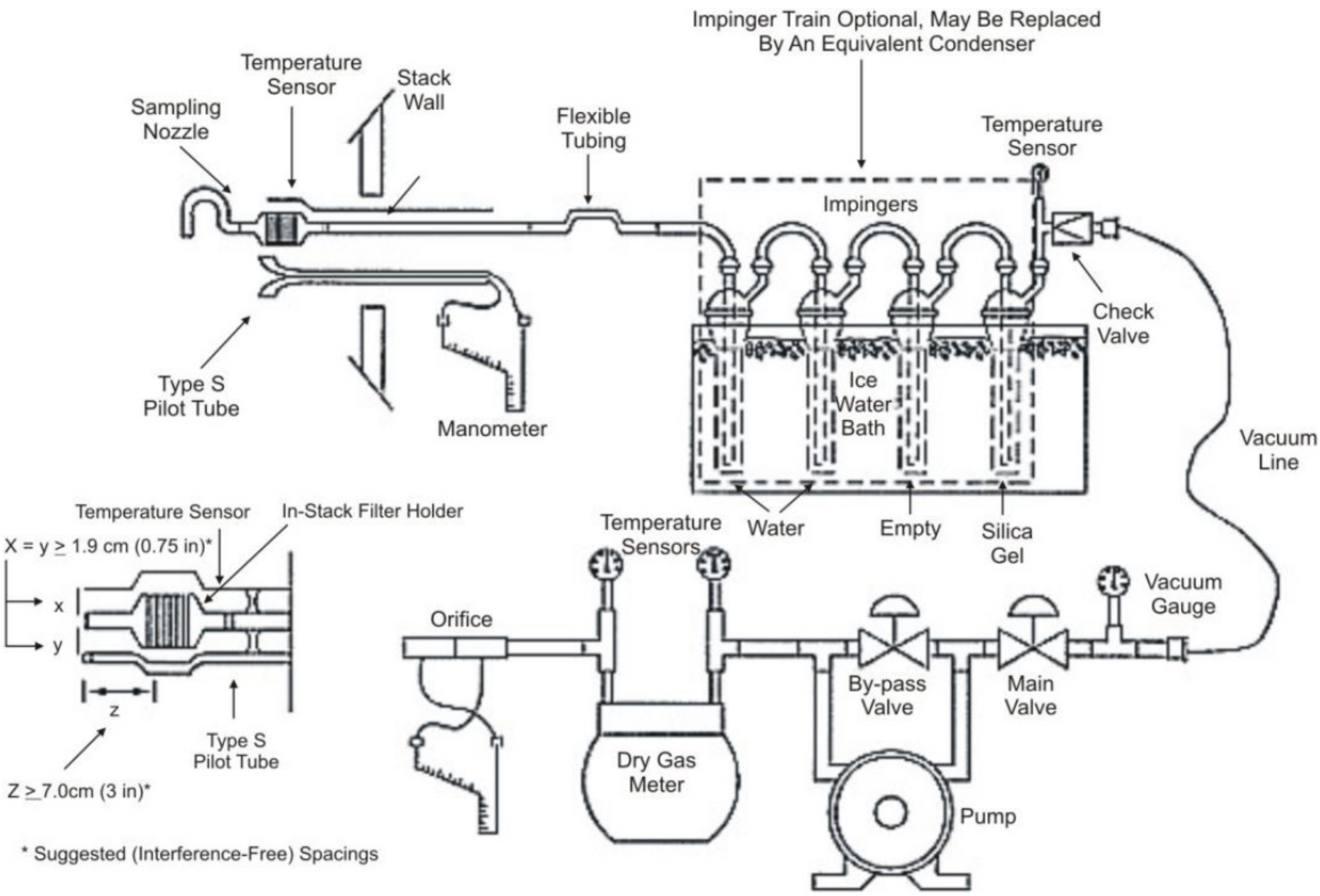

Figure 1: *Particulate Matter Sampling Train with In-Stack Filter – Source, EPA Method 17*

Normally the gas has to be sampled at multiple points within the sampling plane, depending on the sampling plane cross-sectional area. This plane is usually divided into equal areas, at the center of which the gas is withdrawn. To determine the particulate concentration in the plane, the nozzle is moved from one sampling point to the other, extracting gas isokinetically at each point. Sampling periods should be equal for each sampling point, resulting in a composite sample. If equal sampling areas cannot be chosen, the sampling period should be proportional to the sampling area.

The number of sampling points is not the only factor affecting the accuracy of a measurement emission. It also depends on the duration of sampling each increment. The reason for this is that the flow of solids at any point is never constant but fluctuates randomly above and below the average value. These random fluctuations are always present even when the plant is being operated under steady conditions (Hawksley et al 1977, p 5).

The sample is extracted through a sampling train, which principally consists of the following; a sampling probe tube with entry nozzle, a particle separator, a gas metering system, and a suction system (Figure.1). below). The particle separator and/ or the gas metering system may be either located in the duct or placed outside the duct.

It is necessary to avoid condensation of the vapor (water, sulphuric acid, etc.) in the sampling train during gas sampling, as condensation will interfere with the particle separation, particulate condition and flow measurement. To this end, the probe tube, the particle separator, and the gas flow measuring device are heated to above the relevant dew-point temperature. The water vapor may intentionally be removed downstream of the particle separator to make use of a dry-gas meter for the measurement of sample gas volume if the water vapor content of the duct gas does not vary appreciably during sampling.

For isokinetic sampling, the gas velocity at the sampling point in the duct must be measured and the corresponding sample gas flow calculated and adjusted. Normally, a pitot static tube is used for the measurement of duct gas velocity. The pitot static tube is utilized to measure the static and differential pressures at each equal area point in the gas stream. The stack gas temperature is also measured at each of these points. Together with an estimate of the gas density (containing carbon dioxide, oxygen and nitrogen for typical combustion process), these values are used to calculate the velocity profiles and volume flow rate of the gas stream present in the stack. If the sample gas flow measuring device is used within the duct, the relation between the measured pressure drop and the pitot static tube differential is simple, facilitating the adjustment to isokinetic conditions.

If the gas metering device is located outside the duct, the calculation of the isokinetic sample gas flow rate is more complicated. The calculation for isokineticity must also include the duct gas density under standard conditions, which may be derived from the dry gas composition and the moisture content.

The temperature and static pressure of the gas in the duct and the gas metering device must also be noted if the sample gas flow is measured after water removal.

After sampling, the collected particulate matter is completely recovered (which can necessitate cleaning of the probe and nozzle), dried and weighed. It is important to note that the filter utilized for the separation of the particulate matter from the gas stream must undergo preconditioning, where it is also dried, cooled and weighed. The difference between the post-weight and pre-weight of the filter will be the mass of the particulate matter collected from the gas stream.

Overview of statistical approach

The approaches to calculating method uncertainty utilized in the "Guide to the Expression of Uncertainty in Measurement" (ISO 1995) (generally known as GUM 1995) are the underpinning methods utilized for analysing the data sets under review. In general, the concept of measurement uncertainty as described in the GUM has been broadly accepted by the measurement community (Robinson 2004).

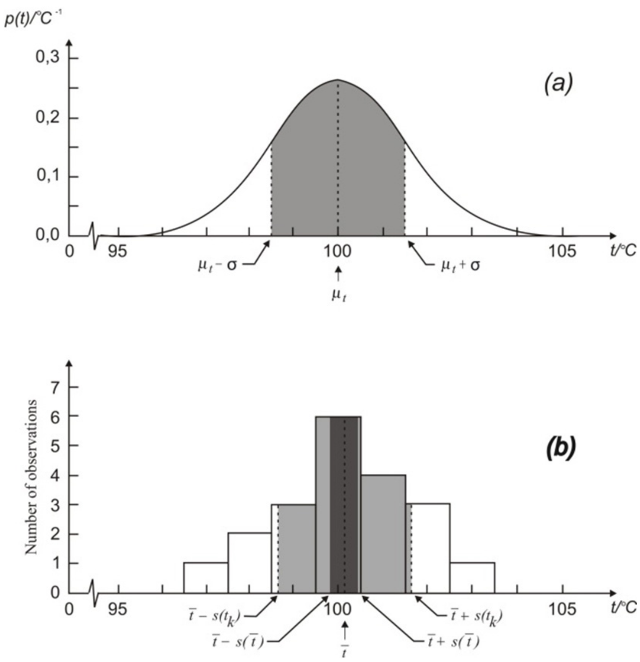

Figure 2: *Graphical illustration of evaluating the standard uncertainty of an input quantity from repeated observations (Source; GUM, 1995)*

The viewpoint of GUM is that all the components that make up the uncertainty of measurement are of the same nature and are to be treated identically (GUM 1995). As a starting point for discussions, a simplified derivation of the mathematical expression for the propagation of standard deviations is utilized, termed in the guide as "the law of propagation of uncertainty". It is important at this point to define what is meant by the term uncertainty. Two definitions are provided: "The word uncertainty means doubt, and thus in the broadest sense the 'uncertainty of measurement' means doubt about the validity of the result of a measurement." (GUM 1995 p 2)

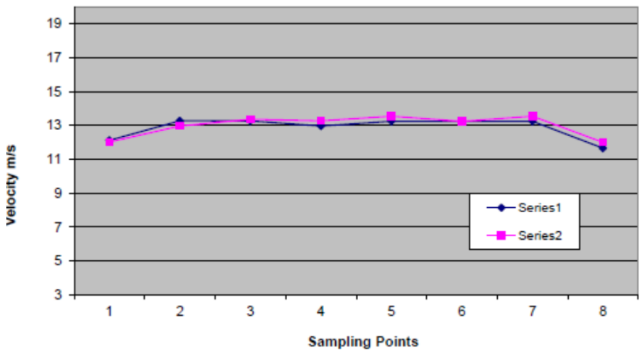

Figure 3: *Velocity profile for test 1 Source A*

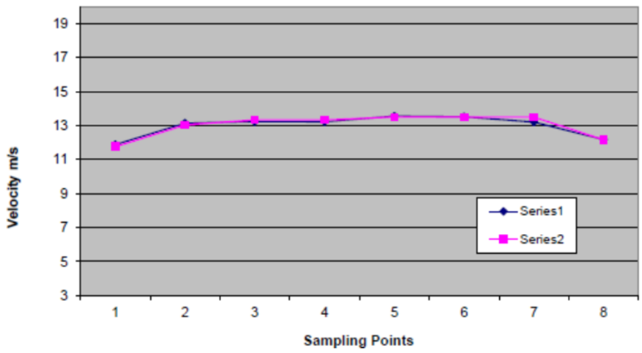

Figure 4: *Velocity profile for test 2 Source A*

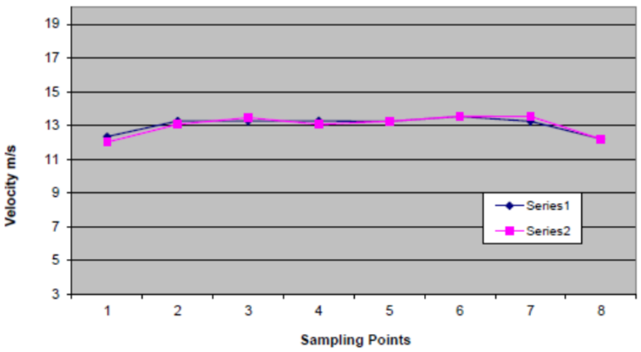

Figure 5: *Velocity profile for test 3 Source A*

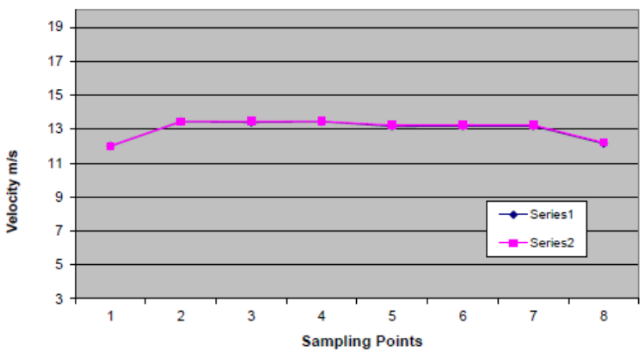

Figure 6: *Velocity profile for test 4 Source A*

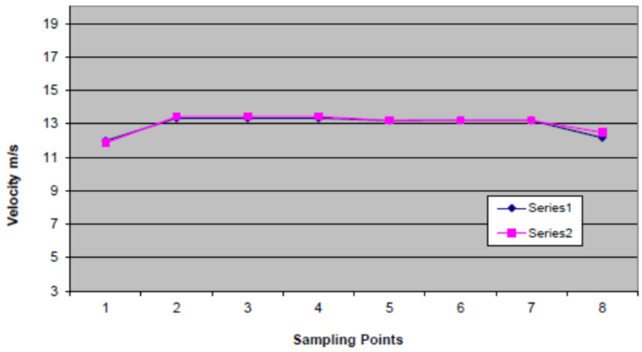

Figure 7: *Velocity profile for test 5 Source A*

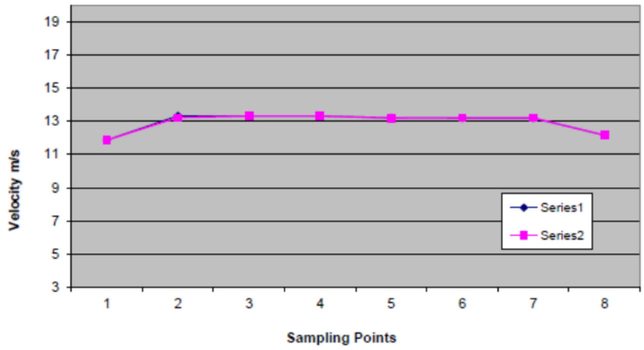

Figure 8: *Velocity profile for test 6 Source A*

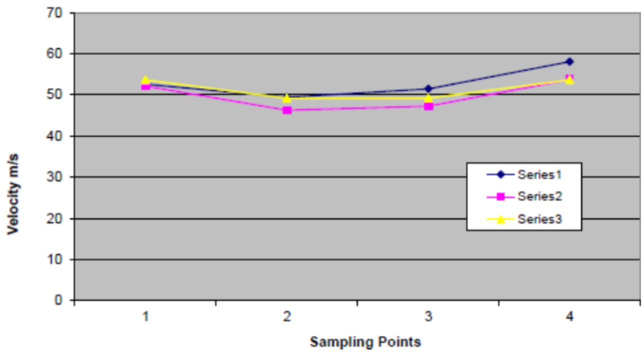

Figure 9: *Velocity profile for test 1 Source B*

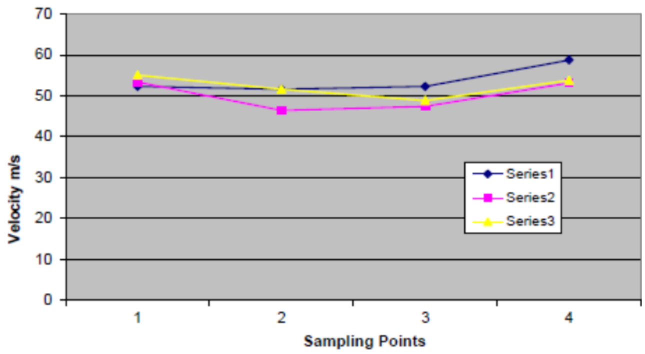

Figure 10: *Velocity profile for test 2 Source B*

"Uncertainty is the unknown (of measurement) parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand (value of a quantity)." (GUM 1995 p 2)

From these definitions, the parameter characterizing uncertainty may be a standard deviation or a multiple thereof. Uncertainty of measurement, in general, comprises of many components.

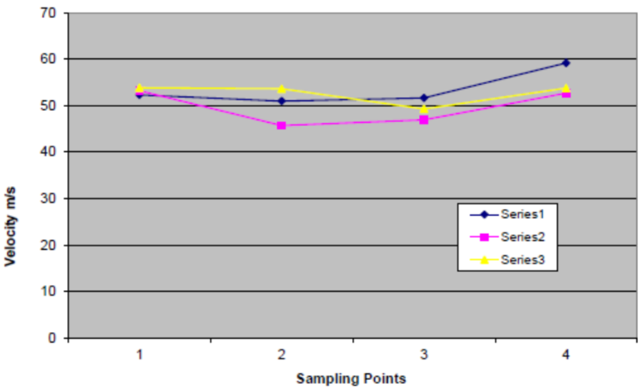

Figure 11: *Velocity profile for test 3 Source B*

Some of these components may be evaluated from the statistical distribution of the results of series of measurements and can be characterized by experimental standard deviations (Figure 2). The other components, which also can be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or relevant information; for example, one can assess the quality of data on adherence to the minimum requirements of a specific standard. If certain of the requirements are met, then one can make specific assumptions about the data. We have utilized this statistical method and applied the principles to both sets of data utilized for the study.

It is important to distinguish between repeatability and reproducibility in conducting a series of measurements and in determining the final outcome and interpretation of the results obtained.

Repeatability: measurements that are taken under the same conditions where the variables and their associated uncertainties are kept constant.

Reproducibility: The attempts to reproduce the results of the repeated observations under differing or varying conditions.

Validation of measured results

If testing was conducted at an unsuitable location, or was carried out under fluctuating plant operating conditions, the validity of the sample may be questioned and the measurement results uncertain (ISO 9096:2003). An assessment of the stability and uniformity of the flow in the flue will determine the suitability/compliance of the sampling location. For this reason the velocity flow profiles for Source A and B have been included to assess the quality and validity of emission results obtained (See Figures 3-11). Series 1, 2 and 3 in the figures are representative of the flow profiles for each sampling port utilized for repeated sampling runs. Source B is a rectangular non-compliant sampling location and it is for this reason the flow profiles will not represent a typical uniform velocity profile as there is significant uneven, non-uniform flow at this sampling location.

Combined uncertainty for measured parameters

The measured parameters for all of the individual tests conducted on Sources A and B are given in Table 1.

If one compares the calculated overall uncertainties for Table 1, one would notice that the non-compliant data set returns a similar overall uncertainty (62.69% RSD) when compared to the compliant stack (62.52-72.98% RSD). The overall uncertainty is also much higher than anticipated; this once again is mainly attributed to the small data sets utilized and the number of external variables that cannot be accounted for (i.e. certain process operating conditions, changes in environmental conditions, etc.)

Due to a lack of sufficient data, normal distribution was assumed for all parameters but could not be statistically verified. All the measured off-gas parameters have been incorporated into table 1 together with the calculated result. For each set of data the following results were calculated in order to derive the final combined expanded uncertainty for each parameter:

Step 1: Tabulate all the raw data results

Step 2: Calculate the sum of all the results

Step 3: Calculate the average for the data set from the sum of the results

Step 4: Calculate the median for the data set

Step 5: Calculate the variance

$(s^2) = \Sigma [(x_i - \bar{x})^2]/(n - 1)$

Where:

s^2 = Variance

Σ = Summation, which means the sum of every term in the equation after the summation sign.

x_i = Sample observation. This represents every term in the set.

$\bar{x}$ = The mean. This represents the average of all the numbers in the set.

n = The sample size. This can be thought of as the number of terms in the set.

Step 6: Calculate the standard deviation

$$s = \sqrt{\frac{\sum(x - \overline{x})^2}{N - 1}}$$

Where:

- S = standard deviation
- x = each value in the sample
- $\bar{x}$ = The mean of the values
- N = the number of values (the sample size)

Step 7: Calculate uncertainty at 95% confidence interval

- Utilise the Student t-distribution table to determine the coverage K factor from the degrees of freedom for the data set for the equivalent 95% confidence interval.

Step 8: Calculate combined standard uncertainty. Each individual uncertainty is calculated as a standard deviation for each individual component. Each standard deviation is then squared and added together. The square root of the sum of the individual uncertainties are then expressed as the combined standard uncertainty as per the equation below.

$$CU = \sqrt{u_1^2 + u_2^2 + \cdots + u_n^2}$$

or

$$CU = (u_1^2 + u_2^2 + \cdots + u_n^2)^{\frac{1}{2}}$$

Where:

- CU = combined uncertainty
- U = uncertainty of individual component

Table 1: *Measured parameters and their estimated uncertainty for Sources A and B.*

ISOKINETIC TEST RESULTS | PLANT COMPLIANT SAMPLING POSITION | DATE 01-Aug-05								
DATA NO.	**Dust [conc] mg/Nm³**	**CO_2**	**O_2**	**Static Pressure**	**Moisture**	**Gas Temp**	**Gas Velocity**	**Gas Density**
1	287.65	11.10	8.20	-1.10	2.33	125.45	12.99	0.75
2	293.30	11.10	8.20	-1.11	3.80	125.65	13.03	0.75
3	315.89	11.10	8.20	-1.05	3.77	127.66	13.13	0.74
4	318.30	11.50	8.10	-1.05	2.30	123.96	13.08	0.75
5	396.23	11.50	8.10	-1.05	2.42	124.69	13.28	0.75
6	428.34	11.50	8.10	-0.98	2.19	126.03	13.22	0.75
PARAMETER								
sum	2039.71	67.80	48.90	-6.34	16.81	753.44	78.73	4.49
average	339.95	11.30	8.15	-1.06	2.80	125.57	13.12	0.75
median	317.10	11.30	8.15	-1.05	2.38	125.55	13.11	0.75
variance	2823.22	0.04	0.0025	0.0018	0.49	1.33	0.01	0.000014
SD	53.13	0.20	0.05	0.04	0.70	1.15	0.10	0.0037
confidence (95%)*	130.18	0.49	0.12	0.10	1.71	2.82	0.25	0.01
% Uncert	15.63	1.77	0.61	4.00	24.94	0.92	0.78	0.50
% Uncert (95% CI)*	38.29	4.34	1.50	9.81	61.09	2.25	1.90	1.22
Combined Standard Uncertainty		53.15						
Combined Expanded Uncertainty		130.221						
Combined Standard Uncertainty % Relative		29.79						
Combined Expanded Uncertainty % Relative		72.98						
*where CI = 95%, K = 2.45, degrees of freedom = 6								
ISOKINETIC TEST RESULTS | PLANT COMPLIANT SAMPLING POSITION | DATE 04-Aug-05								
DATA NO.	**Dust [conc] mg/Nm³**	**CO_2**	**O_2**	**Static Pressure**	**Moisture**	**Gas Temp**	**Gas Velocity**	**Gas Density**
1	159.60	11.50	8.10	-1.20	4.00	123.51	13.19	0.75
2	188.86	11.50	8.10	-1.20	2.73	125.63	13.14	0.75
3	192.32	11.50	8.10	-1.20	4.11	125.45	13.11	0.75
4	218.84	11.40	8.20	-1.07	5.26	122.91	13.12	0.75
5	236.85	11.40	8.20	-1.07	5.08	123.69	13.17	0.75
6	254.29	11.40	8.20	-1.05	4.63	124.00	13.12	0.74
PARAMETER								
sum	1250.76	68.70	48.90	-6.79	25.81	745.19	78.85	4.49
average	208.46	11.45	8.15	-1.13	4.30	124.20	13.14	0.75
median	205.58	11.45	8.15	-1.14	4.37	123.85	13.13	0.75
variance	1007.68	0.0025	0.0025	0.0047	0.70	1.01	0.0008	0.000014
SD	31.74	0.05	0.05	0.07	0.84	1.00	0.03	0.0037
confidence (95%)*	77.77	0.12	0.12	0.17	2.06	2.46	0.07	0.01
% Uncert	15.23	0.44	0.61	6.07	19.52	0.81	0.22	0.50
% Uncert (95% CI)*	37.31	1.07	1.50	14.86	47.82	1.98	0.54	1.22
Combined Standard Uncertainty		31.77						
Combined Expanded Uncertainty		77.8393						
Combined Standard Uncertainty % Relative		25.52						
Combined Expanded Uncertainty % Relative		62.52						
*where CI = 95%, K = 2.45, degrees of freedom = 6								
ISOKINETIC TEST RESULTS | PLANT NON-COMPLIANT SAMPLING POSITION | DATE 10-Nov-05								
DATA NO.	**Dust [conc] mg/Nm³**	**CO_2**	**O_2**	**Static Pressure**	**Moisture**	**Gas Temp**	**Gas Velocity**	**Gas Density**
1	1694.52	23.00	11.00	-1.00	9.68	93.17	52.44	0.83
2	1813.39	22.00	11.00	-1.00	12.89	95.00	53.50	0.82
3	2051.77	22.00	12.00	-1.08	12.72	95.75	53.39	0.82
PARAMETER								
sum	5559.68	67.00	34.00	-3.08	35.29	283.92	159.33	2.47
average	1853.23	22.33	11.33	-1.03	11.76	94.64	53.11	0.82
median	1813.39	22.00	11.00	-1.00	12.72	95.00	53.39	0.82
variance	22064.74	0.22	0.2222	0.0014	2.17	1.17	0.23	0.000022
SD	181.93	0.58	0.58	0.05	1.81	1.33	0.58	0.01
confidence (95%)*	578.53	1.84	1.84	0.15	5.74	4.22	1.85	0.02
% Uncert	9.82	2.59	5.09	4.50	15.35	1.40	1.10	0.70
% Uncert (95% CI)*	31.22	8.22	16.20	14.31	48.83	4.46	3.49	2.23
Combined Standard Uncertainty		181.94						
Combined Expanded Uncertainty		578.5778						
Combined Standard Uncertainty % Relative		19.71						
Combined Expanded Uncertainty % Relative		62.69						
*where CI = 95%, K = 3.18, degrees of freedom = 3								

This small study has confirmed the findings of a comparable but larger project which came to similar conclusions (discussed in section 3.2). The Dutch study mentioned in ISO 9096:2003 collected much larger data sets than the one used in this study, yet had very high levels of uncertainty when trying to calculate an overall uncertainty for the entire data set. Prior to the Dutch field-based study being undertaken (ISO 9096:2003 p38), a sensitivity analysis was conducted of the uncertainty of the entire document. "This led to the conclusion that the determination of the waste gas velocity (i.e. mispositioning of the pitot tube) had contributed most to the total measuring uncertainty" (ISO9096:2003 p38). In turn, a non-complying sampling location can also have a significant effect on the velocity profile (See figures 3 – 11) and ultimately affect the total measurement uncertainty in the same way as a mispositioned pitot tube.

Discussion

The statistical analysis of the data reveals that no conclusive opinions can be made about the data sets utilized. An estimate of the overall uncertainty was attempted but the results were not conclusive as not enough data were obtained to enable any valid statistical inferences to be made.

After applying the statistical methodology to the data sets, it was concluded that the data sets were far too small. Ideally 50 – 100 or more samples need to be included in each of the data sets (ISO GUM 1995). Unfortunately, obtaining a large enough data set has not been possible due to budget constraints and the cost and logistics of conducting the sampling. The standard deviation for the test results is relatively high over the range of results and this is mostly attributed to the small data sets obtained.

Due to the nature of field sampling, not all variables can be controlled. The samples are all taken at different times and reasonable care is taken to ensure that the sampling is conducted under similar plant operating conditions, however natural fluctuations and process variations under normal operations inevitably occur and thus cannot be adequately controlled. Although this is the case for each individual source sampled, significant variation in the results still occurs as a result of a large number of input variables involved i.e. sampling procedure, process operation, plant and prevailing environmental conditions all of which have an influence on the repeatability and reproducibility of the results.

The influence of turbulent flow is said to also have a large negative effect on the overall result. Attempts to calculate Reynolds numbers for the various flow profiles to ascertain whether the flow was laminar were conducted. The compliant as well as the non-compliant sampling positions both showed Reynolds numbers in the turbulent range. ISO 9096:1992 and 2003 does not require laminar flow but states that the flow in the duct must be as stable and uniform as possible. To achieve laminar flow, one needs to have very low flow rates. As the flow rates of a typical enclosed flue gas stream are high, (ranging between 5 – 30 m/s; for this study the velocity range was between 11.5 – 50m/s) obtaining true laminar flow is almost impossible. It is for this reason that the application of the Reynolds number did not confirm compliance or non-compliance of the sampling positions.

An alternative method/tool to utilizing statistical techniques is to use qualitative estimates of uncertainty based on experience, reasonable estimates of errors and uncertainties and adherence to the minimum requirements of the ISO 9096:1992 and 2003. The result of this approach has been the development of a sampling suitability matrix. This matrix consists of a table with all the minimum requirements, as set out in ISO 9096:2003 pg.31 (see also table 2). From the table, the accuracy and minimum requirements for all the apparatus and sampling conditions are given.

Utilizing this method, once the sampling survey has been completed the sampling specialist will check each of the components for compliance. A rating scale has been devised by the author for the influence each component is estimated to have on the final results. These values have largely been derived from experience in the field and the ability for the sampling specialist to control certain variables (systematic errors).

Sampling suitability matrix

All the measurement variables have been tabulated and categorized (see Table 2). The measurement variables have been placed into three categories namely: sampling location, equipment used for dust collection, and equipment for flue gas characteristics (ISO 9096:2003, pg. 31). Each variable has been given a rating out of ten, the higher the number out of ten, the greater the influence of the variable on the uncertainty of the final sampling results. The rating is subjective; the principle behind the rating of each variable is the ability of the test technician to control that specific variable. The less control the test technician has over the variable, the higher the score or rating that is assigned to the applicable variable

From Table 2, the accuracy for each component of the measurement variables is given. Once the sampling survey has been conducted, the sampling specialist will check each of the components for compliance to the minimum requirements (ISO 9096:2003). The ratings are based on a sliding scale with a score of ten having been estimated to have the most impact on the final measurement uncertainty and a rating of one having the lowest impact on the final measurement result. A zero value indicates that the plant is not in compliance for that parameter and therefore the overall points scored will be lowered. Once all the components or variables have been checked for compliance, the sampling specialist will calculate each specific component rating. The sampling specialist will input all the results and ratings into the sampling suitability table that will estimate the quality of the final measurement result as excellent, fair or poor see the last column of table 2.

***Table 2:** Sampling suitability matrix*

Summary of requirements - Apparatus and sampling conditions					
SAMPLING LOCATION	**Approx. Value**	**Measured Value**	**Compliance y/n**	**Rating**	
Flow angle	<15°			10	P
Pressure difference (pitot tube)	> 5 Pa			10	P
Ratio of max gas velocity to min gas velocity	3:1			10	P
Negative flow	None			10	P
Straight length before the sampling plane	> 5 hydraulic diameters			9	P
Straight length after the sampling plane	> 2 hydraulic diameters			9	P
Straight length before emission point	> 5 hydraulic diameters			9	P
Number of sampling points	dependant on duct size			9	P
EQUIPMENT FOR DUST COLLECTION					
Alignment of the nozzle	10%			8	FS
Isokinetic Criteria	+15% and -5 %			8	FS
Leak test	< 2%			8	FS
Condenser, drying tower: residual gas moisture	< 10 g/m³			7	FS
Gas meter volume measurement uncertainty	2%			7	FS
Absolute pressure measurement uncertainty	1%			7	FS
Absolute temperature measurement uncertainty	1%			7	FS
Filter efficiency (test aerosol 0,3um)	> 99.5 %			6	EQ
Filter material (adsorption of components)	No reaction or adsorption			6	EQ
Nozzle straight length before the first bend	> 30 mm			5	EQ / P
Nozzle tip: distance to obstacles	> 50 mm			5	EQ / P
Nozzle: Length with constant internal diameter	> 10 mm			4	EQ
Nozzle: variation in diameter angle	< 30°			4	EQ
Nozzle Internal diameter	> 4mm			4	EQ
Nozzle area: measurement uncertainty	10%			4	EQ
Elbow: Radius of the bend	> 1,5 d			4	EQ
Balance resolution (mg)	0.01mg to 0.1mg			3	L
Weighing uncertainties	< 5% of the LV for process			3	L
Thermal stability (filter)	> 8h			3	L
Overall Blank Value	< 10% LV or 2 mg/m³			3	L
Sampling time measurement uncertainty	5 secs			2	FS
Linear measurement uncertainty	1% duct .2mm / 5% Nozzle			2	FS
EQUIPMENT FOR FLUE GAS CHARACTERISTICS					
Absolute temperature	1%			1	C
Flue gas density	0,05 kg/m³			1	C
Total possible Score				188	
Validity of Results obtained					%
Excellent (Fully compliant)				188	1.00
Fair (mostly compliant)				150	0.80
Poor				60	0.32

Key:
P: Plant Restrictions
FS: Field Sampling Restrictions
EQ: Equipment Restrictions
L: Laboratory Restrictions
C: Calculated / Measured in the Field

Discussion

From the sampling suitability matrix table, one can deduce that the restrictions of the plant as well as field sampling restrictions, time constraints, plant availability, extreme operating conditions, sampling location restrictions and access to the sampling position have the biggest impact on the final data quality, and therefore have the highest rating (the more requirements in terms of the sampling location and plant restrictions that do not comply, the greater the impact on the results). Equipment restrictions such as limits of detection, calibration and verification of sampling train components, and resolution of sampling train components utilized, may have a significant impact on the results; these variables thus received a moderate rating in terms of impacting the final data quality. The laboratory analyses and calculated values have the least impact on the final results as these are the variables that can be best controlled by the sampling specialist and laboratory personnel.

The application of the sampling suitability matrix to each data set seems to correlate well when applied to both surveys (Source A and Source B) utilized in this project. The sampling suitability matrix confirmed that the compliant plant (Source A) should generate good reliable data while the results for the non-compliant plant (Source B) agree with the results of the sampling suitability matrix in that the results may not be as reliable as the fully compliant plant that was surveyed.

The potential importance of applying the sampling suitability matrix table to post survey results cannot be underestimated. The table's inclusion in the final emissions report will go a long way to highlighting specific problem areas with regards the measurements. The requirement of completing this suitability table will provide a tool for the sampling experts to identify areas of improvement that need to be made to sampling conditions or equipment. It will also go a long way to highlighting the need for identifying suitable sampling locations, stable operating conditions etc. to be provided for by the plant personnel.

Summary and conclusions

When conducting sampling surveys to obtain source emissions data, it has been suggested that the greatest components of error are those that are out of control of the sampling specialist (Random Error); plant operating conditions, environmental conditions, and the non-compliance of the sampling location to the minimum requirements as set out in ISO 9096:1992 and 2003, etc.

The subsequent comparison and analyses of the data between the compliant and non-compliant sampling scenarios has confirmed these suspicions. Once these findings had been established, it was endeavored to find ways through statistical treatment of the data to estimate the uncertainty of the measurements when faced with a non-compliant sampling position.

Determining the measurement uncertainty quantitatively from the analysis of the data in this project was not feasible. The reason for this was that the data sets used in the statistical analysis were too small to derive any conclusions from the results. Due to the labour-intensive, time consuming nature and budgetary constraints involved in trying to obtain sufficient quality data, an alternative qualitative approach was deemed more suitable for the purposes of this study, in order to estimate the uncertainty or overall quality of the final emission data reported. The results of this approach include the development of the sampling suitability matrix which was developed through careful analyses of the minimum requirements as set out in ISO 9096:1992 and 2003 and vast sampling experience. Values have been assigned to all the components and variables that have a significant impact on the quality of the data as set out in ISO9096:1992 and 2003.

The end result is a sampling suitability matrix table that allows the sampling specialist to analyse each component of the sampling process and assess whether adherence to the minimum requirements have been met. In instances where the minimum requirements for a specific component have not been met, a specific rating has been given to that component which corresponds to the specific impact of its non-compliance on the final emission data reported.

It should be noted that the ratings used are subjective. The matrix can however give a good indication of the quality of the data reported, in the absence of statistically validated data. This is done through careful consideration of the significance and impact that each non-compliance has on the final result.

In conclusion, the sampling suitability matrix would prove to be a valuable tool in assessing final emissions figures that are reported for sampling campaigns in the future. Even though the original goal of the project was not achieved in terms of quantifying the uncertainty of emissions data, the sampling suitability matrix will be able to give more insight to the client as well as sampling experts in the field on the interpretation and reliability of the emissions figures reported. This information will go a long way in helping the decision-making process with regards to ensuring environmental compliance. It will give insight into whether enough good quality data have been provided, or whether the results are questionable, resulting in the need for addressing changes to the prevailing sampling conditions, sampling techniques utilized or whether an alternative sampling approach is needed to obtain good quality data. Further study into the quantification and estimation of source emission uncertainty will need to be done with larger data sets to enable better interpretation of the results and to allow for a meaningful statistical analysis to be performed.

As mentioned in the introduction, the current trend by industry is to save costs by doing only what is required to comply with the relevant environmental standards. This study has shown this behavior to be short sighted and it may result in much larger costs in the long run and non-compliant permit conditions prevailing as a result of poor data quality.

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Air quality indicators from the Environmental Performance Index: potential use and limitations in South Africa

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Abstract
In responding to deteriorating air quality, many countries, including South Africa, have implemented national programmes that aim to manage and regulate ambient air quality, and the emissions of air pollutants. One aspect within these management strategies is effective communication to stakeholders, including the general public, with regard to the state and trend of ambient air quality in South Africa. Currently, information on ambient air quality is communicated through ambient mass concentration values, as well as number of exceedances of South African National Ambient Standards. However, these do not directly communicate the potential impact on human health and the ecosystem. To this end, the use of air quality indicators is seen as a potential way to achieve communication to stakeholders in a simplified, yet scientifically defensible manner. Air quality indicators and their source data from the Environmental Performance Index (EPI) were interrogated to understand their potential use in South Africa. An assessment of four air quality indicators, together with their source data, showed improvements in air quality over the time period studied, though the input data do have uncertainties. The source data for the PM indicators, which came from a global dataset, underestimated the annual $PM_{2.5}$ concentrations in the Highveld Priority Area and Vaal Triangle Airshed Priority Area over the time period studied (2009-2014) by ~3.7 times. This highlights a key limitation of national-scale indicators and input data, that while the data used by the EPI are a well-thought out estimate of a country's air quality profile, they remain a generalised estimate. The assumptions and uncertainty inherent in such an ambitious global-wide attempt make the estimates inaccurate for countries without proper emissions tracking and accounting and few monitoring stations, such as South Africa. Thus, the inputs and resultant indicators should be used with caution until such a time that local and ground-truthed data and inputs can be utilised.

Keywords
Air quality indicators, air quality management

Introduction
Globally, air pollution is of concern and has deteriorated in many areas due to emissions from anthropogenic activities including industrial and vehicular activities, as well as from emissions from natural sources such as biomass burning. The current state of air quality has become a major threat to the health and wellbeing of people, as well as the environment in many areas around the world. In responding to deteriorating air quality, many countries, including South Africa, have implemented national programmes that aim to manage and regulate ambient air quality, and the emissions of air pollutants. In South Africa, the approach includes the declaration of priority areas for air quality management, development of national air quality standards, and an air quality monitoring programme. The aim of these programmes is to reduce air pollution-related illnesses and conditions.

One aspect within these management strategies is effective communication to stakeholders, which includes the general public, with regard to the state and trend of ambient air quality in South Africa. Currently, information on ambient air quality is communicated through ambient mass concentration values, as well as number of exceedances of South African standards. However, these do not directly communicate the potential impact on human health and the ecosystem. To this end, the use of air quality indicators is seen as a potential way to achieve communication to stakeholders in a simplified, yet scientifically defensible manner.

Environmental Performance Indicactor
The Environmental Performance Index (EPI) was developed by the Yale Centre for Environmental Law and Policy at Yale University and the Centre for International Earth Science Information Network at Columbia University (http://epi.yale.edu). The EPI aggregates over 20 indicators relating to national environmental data.

The EPI assesses two objectives, namely Environmental Health and Ecosystem Vitality. The Issue Category of "Air Quality" is within Environmental Health, though in previous EPI reports there have been Air Quality issues within the Ecosystem Vitality objective.

There have been a variety of indicators in the Air Quality issue category in the history of EPI, with recent years focussing on particulate matter (PM) and household air pollution. The EPI 2016 assessment includes an indicator on exposure to nitrogen dioxide (NO_2), and previous EPIs (e.g. 2008) have included indicators on ground-level ozone for health and for ecosystems considerations. For developing local indicators, this suite of present and historical EPI indicators should be assessed for their relevance to local air quality issues and policy priorities, and for the availability and reliability of local data.

For this study, the following indicators were selected to ground-truth air quality aspects for South Africa. This assessment is not comprehensive of all air quality indicators from the EPI, however focussed on selecting indicators that assessed different pollutants and data sources, as well as highlighting some of the pollutants and emission sources of concern in South Africa. These indicators provide information on the potential impact on human health and on ecosystems. In this analysis, only the following four indicators (that form part of the EPI) were considered. The objective that the indicator was included under in the EPI is listed in parenthesis below.

- HAP = Household Air Pollution (environmental health) - Percentage of population using solid fuel as the primary cooking fuel (%)
- SO2CAP = Air pollution (ecosystem vitality) - Sulphur dioxide emissions per capita
- SO2GDP = Air pollution (ecosystem vitality) - Sulphur dioxide emissions per Gross Domestic Product (GDP)
- PM25 = Air Pollution (environmental health) - Population weighted exposure to $PM_{2.5}$ ($\mu g/m^3$)

The SO2CAP and SO2GDP are not included in the current (2014 or 2016) estimations of EPI; they are nonetheless important indicators for South Africa and thus included here.

This study interrogated the input data into the EPI and compared this input data to publically available local data. This comparison will help to gain a better understanding of the robustness of the input data, and in turn, the indicators. These findings assisted in understanding the potential uses and limitations of the indicators, as well as provided insight into the state of air quality in the country.

Methods

EPI input data

EPI output values for indicators are reported on a national scale. The website does give links to the underlying data sources, and those sources are described here (http://epi.yale.edu/).

EPI: Solid fuel use for cooking data

The HAP data are derived from Bonjour et al. (2013), which were based upon data from the WHO Household Energy Database (2012). The EPI indicator is defined as the percentage of population using solid fuel for cooking. The percentage of population that are exposed to household air pollution was assumed to be the same as the percentage of households using solid fuels; thus the percentage of households using solid fuels is assessed and compared. These data are based on national surveys, which do report percentage of households using solid fuels for cooking.

EPI: SO_2 emissions

The SO2GDP and SO2CAP were last reported in EPI 2012, and those are the input data reported here. The SO_2 aspect is represented by total anthropogenic emissions for a country. The input SO_2 emissions were based on the research detailed by Smith et al. (2011), in which global bottom-up inventories (primarily through mass balance for combustion and metal smelting) were created for each country and constrained by any available locally derived emissions measurements or estimates. The original inventory covers years 1850-2005 and is reported in 10 year increments in Smith et al. (2011). The source sectors considered were coal combustion, petroleum combustion, natural gas processing and combustion, petroleum processing, biomass combustion, shipping bunker fuels, metal smelting, pulp and paper processing, other industrial processes, and agricultural waste burning.

EPI: Population and GDP data

Indicator SO2GDP requires that GDP be converted to international dollars using purchasing power parity rates; for the 2012 EPI, 2005 international dollars were used. These were sourced from the World Development Indicators (indicator NY.GDP.MKTP.PP.KD; World Bank, 2011) and covered the period 1980-2011. SO2CAP requires country population data and this was also sourced from the World Development Indicators (indicator SP.POP.TOTL; World Bank, 2011) and covered the period 1960-2010.

EPI: Ambient $PM_{2.5}$ simulated concentrations

The PM25 EPI indictor quantifies the population weighted exposure to $PM_{2.5}$ for the country. This indicator uses $PM_{2.5}$ ambient concentrations that were originally estimated by Van Donkelaar et al. (2015) and are available online (ACAG, 2016). The datasets used here were the "All composition" satellite-derived $PM_{2.5}$ at a relative humidity of 35% for a three-year running median.

The methodology used to estimate surface $PM_{2.5}$ concentrations was included in the method used in estimating the Global Burden of Disease that is attributable to PM (Burnett et al., 2014; Brauer et al., 2012). The methods are not the same, however, as Brauer et al. (2012) did use multiple data sources, including ground-based data.

The methodology followed to estimate $PM_{2.5}$ ambient concentrations is detailed in Van Donkelaar et al. (2010), Van

Donkelaar et al. (2015) and Boys et al. (2014). Briefly, aerosol optical depth (AOD) from the combination of Moderate Resolution Imaging Spectroradiometer (MODIS), Multiangle Imaging Spectroradiometer (MISR) and Sea-viewing wide field-of-view sensor (SeaWIFS) satellite instruments were used together with global chemistry transport model simulations using the Goddard Earth Observing System model with Chemistry (GEOS-Chem). Ground-level concentrations of $PM_{2.5}$ were estimated by developing an AOD conversion factor (accounting for aerosol size, aerosol type, diurnal variation, relative humidity and the vertical structure of aerosol extinction) based on GEOS-Chem simulations. The results were daily values coinciding with satellite overpass time; these were aggregated into three year moving median values. The median values were used to reduce the noise in the data from the satellite retrievals (Van Donkelaar et al., 2015).

Local data

This section details the local data sources that were compared to the "international" data from the EPI. As discussed in the section below, the national SO_2 and solid fuel use data for the EPI and the "local" data have similar sources.

Local: Solid fuel use for cooking data

The local data were provided by the South African Department of Environmental Affairs (DEA) and included information on the distribution (in percentage) of households that use domestic fuels (paraffin, wood, and coal) for household activities such as cooking, heating and lighting. These data were compiled from the 2014 General Household Survey data from Statistics South Africa (Stats SA) (Statistics South Africa, 2015).

Figure 1 displays the percentage of households using paraffin, wood or coal for cooking in South Africa for 2002-2014. For comparison to the EPI, the percentage of households using solid fuels for cooking was defined as those using coal and wood. It should be noted that EPI includes the burning of crop residues, dung and charcoal, which were not included here due to lack of local data.

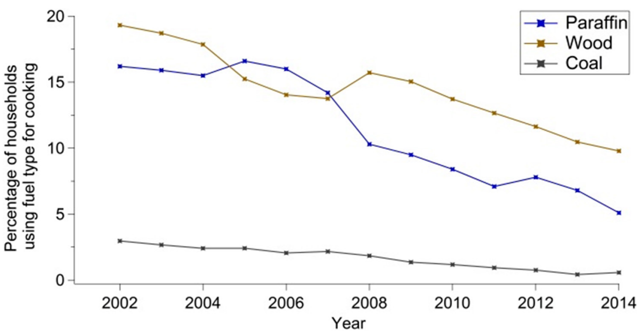

Figure 1: Stats SA data for percentage of households in South Africa using coal (grey line), wood (brown line) or paraffin (blue line) for cooking.

Local: SO_2 emissions

There are no locally derived data for a complete national SO_2 emission inventory. As detailed in section 2.1.2, the EPI used data from Smith et al. (2011). However, there is much room for improvement regarding SO_2 emissions as there are high levels of uncertainty in Smith et al. (2011) estimates for South Africa. This is due to lack of local emissions reporting, and in uncertainty due to assumptions in bottom-up calculations such as fuel sulphur content and activity data (i.e. the actual amount of fuel used). Smith et al. (2011) specify uncertainties of up to 54% for South Africa (included in the "Other Countries" grouping for uncertainty analysis) for the sources included.

Klimont et al. (2013) built on the methodology and work by Smith et al. (2011) and estimated global SO_2 emissions through the Greenhouse Gas–Air Pollution Interactions and Synergies (GAINS; Amann et al. 2011) model for the period 2000-2011. This period is relevant to assessing a South African emissions profile due to rapid development. These published outputs are used in this comparison.

Klimont et al. (2013) also report a still significant amount of uncertainty may exist in this newer inventory; however, a quantitative estimate was not produced. The assumption around this large uncertainty was based on the inclusion of regional activity and fuel data from developing countries and within the international shipping sector. Ideally, a locally derived estimate, which includes local fuel specifications and activity data, must be provided to the general public such that researchers can include these data into their studies and indices.

Local: Population and GDP data

Economic and demographic data are readily available for most countries through either the World Bank or United Nations Populations Division. While it is possible to refine the World Bank Development Indicator population estimates using local census data, the difference is marginal for years 1996 (1.5% underestimate), 2001 (0.2% overestimate) and 2011 (0.4% underestimate) when compared to Stats SA census releases (Statistics South Africa, 2012). In order to have a full time series of population data, the EPI data source for population were used (World Bank, 2011).

In evaluating and comparing the SO2GDP indicator it is necessary to use the same units specified within the EPI methodology. The 2012 EPI methodology specifies GDP in 2005 international dollars. The only readily available data representing this are the World Development Indicators (same as used in EPI); these data could not be easily found from a local source directly. It is assumed here that these represent accurate local estimates of GDP and thus were used in calculating the local indicator (indicator SP.POP.TOTL; World Bank, 2011).

Ambient $PM_{2.5}$ monitored data

The South African Air Quality Information System (SAAQIS) data were used to ground truth the EPI $PM_{2.5}$ data to verify its level of accuracy. The SAAQIS data used were for the Vaal Triangle Airshed Priority Area (VTAPA) and DEA Highveld Priority Area (HPA) air quality monitoring networks. The VTAPA network has been running since 2007, and HPA network since 2008. The networks have a relatively continuous monitoring record, and the measured data are quality controlled and managed by the South African Weather Service (SAWS) through the SAAQIS. The networks are in priority areas, and thus are in the more polluted areas of South Africa.

The $PM_{2.5}$ data were provided by SAAQIS as one hour averages for 1 Jan 2008 – 1 October 2015. These data were quality checked (QC) by CSIR, and then averaged to monthly values, and processed to a corresponding three year moving median as reported in EPI data. The quality control included removing negative values and repeating values. Table 1 displays the number of data points (N) before the QC procedure was applied and after the QC procedure was applied. Further analyses were only performed on the valid hourly values (i.e. after the QC procedure was applied).

It is best practice when averaging monitored data to use a "data completeness threshold." This threshold indicates the percentage of data that must be present in order to derive a representative average. For example, for a 70% data completeness rule, if fewer than 70% of 1-hour $PM_{2.5}$ data were recorded in one day, then the daily average could not be calculated and would be left blank. In this analysis, thresholds from 75% to 50% were applied and tested to calculate a three year moving median. However the loss of data was large and analysis presented for this criterion would not have been possible at all sites. Thus, no threshold was applied when averaging the 1-hour values from SAAQIS for this analysis.

Table 1: *Number of data points (N) per station before QC was applied and after QC was applied.*

Site		Lat	Lon	N (before QC)	N (after QC)
HPA	Ermelo	-26.4934°	29.9681°	55 949	55 949
	Hendrina	-26.1509°	29.7168°	39 611	39 592
	Middelburg	-25.7961°	29.4636°	53 438	53 419
	Secunda	-26.5486°	29.0801°	52 063	52 028
	Witbank	-25.8778°	29.1887°	48 789	48 789
VTAPA	Diepkloof	-26.2507°	27.9564°	42 939	42 737
	Kliprivier	-26.4203°	28.0849°	48 762	48 755
	Sebokeng	-26.5878°	27.8402°	41 739	41 725
	Sharpeville	-26.6898°	27.8678°	51 685	51 474
	Three Rivers	-26.6583°	27.9982°	45 852	45 803
	Zamdela	-26.8449°	27.8551°	57 731	57 580

Figure 2 shows the geographical location of the VTAPA and HPA monitoring stations (as points with names of stations indicated) on the 10 km x 10 km grid from the $PM_{2.5}$ data used by the EPI. The $PM_{2.5}$ 3-year running median from each site was compared to the corresponding EPI value from the grid cell where the site is located.

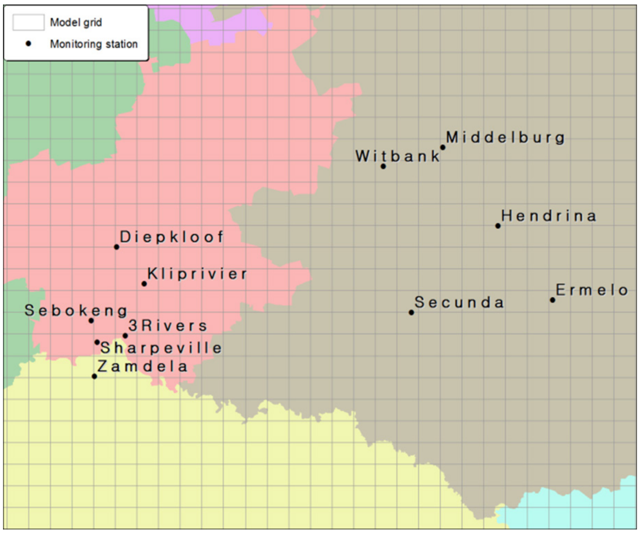

Figure 2: *Map of SAAQIS monitoring stations as points with their names indicated on the 10km resolution model grid of the EPI $PM_{2.5}$ input data. The colours indicate the provinces. The VTAPA monitoring stations are on the west and the HPA are on the east.*

Results and Discussion

Overview of South Africa's standing in the Air Quality Issue Category

The scoring of countries' performance within the EPI is relative to the top-performing country, which receives a score of 100. The other countries' indicator scores are normalised to this top-performer. Thus in the score, a larger number indicates better performance. The top-performing country also receives a rank of 1, thus in rank a lower score indicates better performance. Scoring and ranking occur at each level within the EPI (i.e. indicators, issue categories, objectives and total score).

As the EPI Issue Category Scores are normalised to the top-performing country, over time, a country can have a worsening score even if the air quality is improving, if other countries are improving at a faster rate.

In the 2016 EPI Air Quality issue category, South Africa's score was reported as 88.84 (out of 100), which led to a ranking of 49 out of 180 countries.

South Africa was calculated to have improved its Air Quality issue category score over the past ten years from 74.47 (resulting in a rank of 61) in 2006. The rank of South Africa for PM25 was 60 in 2006, and fell to 69 in 2016. For the HAP indicators, the rank improved from 114 in 2006 to 94 in 2016.

Compared to sub-Saharan Africa's performance as a region, South Africa's 2016 Air Quality score was 18.98 points higher than the region's average score. Thus according to EPI, in general, South Africa for this issue category is performing well for the region, and has on average been improving.

HAP

Figure 3 displays the comparison of the EPI input data and local Stats SA data for the percentage of households using solid fuels for cooking in South Africa. The two datasets compare well, which was expected as the EPI input data source does rely on national surveys. Figure 3 also does highlight the large decrease in households who report using a solid fuel as their primary source for cooking, which can have positive implications for indoor and ambient air quality.

A limitation in these data is that the Stats SA data are limited to primary fuel only. In South Africa, low-income households rely on multiple fuels (e.g. Madubansi and Shackelton, 2007; Llyod et al., 2004; Thom, 2000; Davis 1998). A national survey found that 48% of South African households rely on multiple fuels for cooking (DoE, 2012). Thus, these data won't capture those who do use solid fuels but do not consider it their primary source, nor those who use multiple fuels.

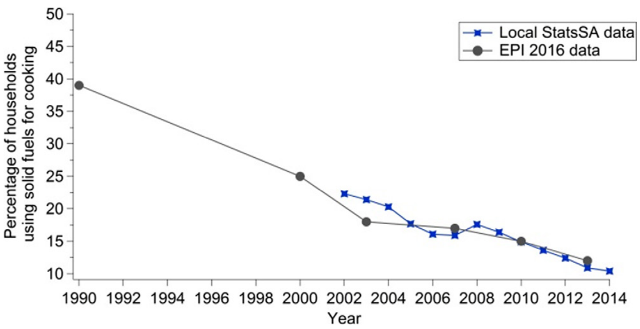

Figure 3: *Percentage of households using solid fuel for cooking from the EPI 2016 input data (grey line) and local Stats SA data (blue line).*

SO2CAP and SO2GDP

There are no local data to compare to the EPI 2012 SO_2 indicators. However, Klimont et al. (2013) has updated the emission estimates from the methodology used in the EPI 2012 indicator; those two datasets are explored here. The economic and population data used to calculate these indicators were the same for EPI 2012 and "Klimont" reported results (Figure 4).

As seen in Figure 4, anthropogenic SO_2 emissions from the datasets agree well, though the Smith et al. (2011) data had a larger dip in emissions in 2001-2002. The anthropogenic SO_2 emissions have been estimated to have increased from 1860 Gg in 1980 to 2795 Gg in 2011. However, during this time, SO2CAP and SO2GDP have both had an overall decreasing trend, though recently the SO2CAP has appeared to hover ~55 kg/person.

The SO2GDP indicator in particular highlights that South Africa's SO_2 economic intensity has decreased, i.e. the GDP growth has been decoupled from the growth emissions in SO_2. This is a positive trend; however as SO_2 emissions are still increasing, there is a continuing negative impact on air quality. However, without a comprehensive national emissions inventory, it is not possible to validate this trend using bottom-up local data.

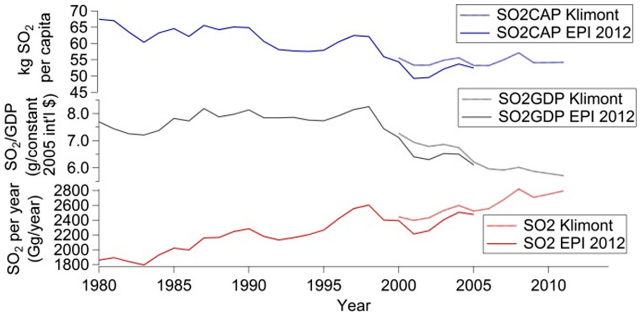

Figure 4: *SO_2 emissions per year (red lines), SO_2 emissions per GDP (black lines) and SO_2 emissions per capita (blue lines)*

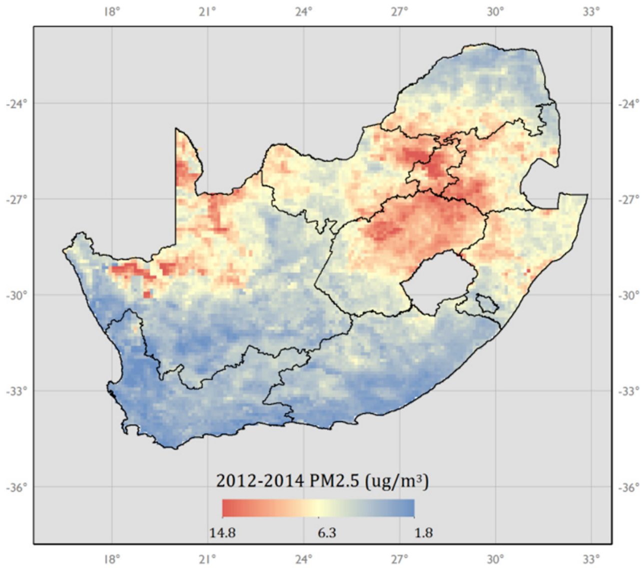

Figure 5: *2013 three year running median of surface $PM_{2.5}$ mass concentrations that were used as input into the EPI.*

PM25

Figure 5 displays the 2013 three-year running median of ground-level $PM_{2.5}$ ambient mass concentrations that was used as input in the PM25 indicator. The running median will be reported by the midpoint year (i.e. 2012-2014 in Figure 5). In this study, the medians for 2010-2013 were compared for all sites. While the magnitude of the medians does change in these averaging periods, the general spatial distribution is similar to Figure 5 across years. This spatial distribution is what would be expected, with higher PM loadings in Gauteng, HPA, and VTAPA, where anthropogenic emissions of air pollution are high. In addition, peaks are seen in the Northern Cape, which in the input dataset are attributed to dust.

Figure 6 displays the average three-year running mean $PM_{2.5}$ concentration of the HPA and the VTAPA stations' for both observations (blue) and EPI database (red). Table 2 displays the $PM_{2.5}$ mass concentrations for the EPI input dataset and from the monitored data from SAAQIS for each station within the HPA and VTAPA (labelled as "Monitored" data). The EPI uses a three-year running median of annual averages. The monitored data from SAAQIS did not have consistent data completeness at all sites across years. This inconsistent completeness may bias the median, as well as inter-annual comparisons. This could particularly have impact in areas that have a strong seasonal

Table 2: *Ground-level $PM_{2.5}$ concentrations (μg/m³) for EPI input data and monitored data from SAAQIS per site of the HPA and the VTAPA*

Network	Site	Year (midpoint three-year running median)	EPI Input annual $PM_{2.5}$ concentrations (μg/m³) (Three-year running median)	Monitored annual $PM_{2.5}$ concentrations (μg/m³) (Three-year running median)	Monitored annual $PM_{2.5}$ concentrations (μg/m³) (Annual average)	Number of monthly values used in annual average
HPA	Ermelo	2010	7.6	30.0	30.0	12
		2011	7.1	29.2	29.2	12
		2012	7.1	28.5	28.5	11
		2013	7.4	24.6	24.6	12
	Hendrina	2010	7.0	20.5	23.3	12
		2011	7.0	18.8	18.8	11
		2012	6.8	18.4	18.4	11
		2013	6.6	18.4	12.5	6
	Middelburg	2010	7.9	22.5	22.2	12
		2011	7.5	23.8	26.0	12
		2012	7.4	23.8	23.8	11
		2013	7.4	19.2	19.2	12
	Secunda	2010	10.2	41.0	40.2	12
		2011	9.3	40.2	46.9	12
		2012	8.9	34.7	34.7	11
		2013	9.3	29.5	29.5	12
	Witbank	2010	8.4	30.2	29.5	12
		2011	7.8	29.5	30.2	12
		2012	7.6	24.5	24.4	11
		2013	7.3	24.3	24.5	12
VTAPA	Diepkloof	2010	10.4	46.8	64.6	7
		2011	10.3	29.7	29.7	9
		2012	9.7	27.0	27.0	11
		2013	9.7	23.0	23.0	12
	Kliprivier	2010	8.6	52.4	52.4	8
		2011	8.0	44.4	44.4	5
		2012	7.4	37.8	37.8	11
		2013	7.5	35.2	30.0	12
	Sebokeng	2010	8.2	51.5	51.5	12
		2011	8.2	51.5	65.0	6
		2012	7.6	33.9	33.9	11
		2013	7.4	30.1	29.3	12
	Sharpeville	2010	9.8	43.8	48.0	9
		2011	9.8	43.0	43.0	5
		2012	9.0	40.7	40.7	11
		2013	8.9	38.7	34.8	12
	Three Rivers	2010	9.6	27.5	32.2	12
		2011	8.8	26.3	21.8	3
		2012	8.7	24.3	26.3	11
		2013	8.7	25.0	24.3	12
	Zamdela	2010	10.4	31.9	36.4	12
		2011	9.8	31.9	31.9	10
		2012	9.2	29.8	29.8	11
		2013	9.2	29.8	29.0	11

cycle, and thus a missing month(s) would strongly impact the annual average and thus the three-year running median. Thus, the annual average per year from the monitored data and the number of monthly values used to calculate each average are also shown in Table 2. While there are differences between the median and the mean values (e.g. 2010 for Diepkloof), it is clear from Table 2 that both values at all sites at all years are much higher than the annual values in the EPI dataset.

Both Table 2 and Figure 6 highlight that the EPI input data underestimates the ground-level $PM_{2.5}$ at all of these sites. On average, the monitored PM is ~3.7 times that used by the EPI, with a range of 2.4 to 6.3 Due to varying data completeness, comparisons between sites and between years were not made.

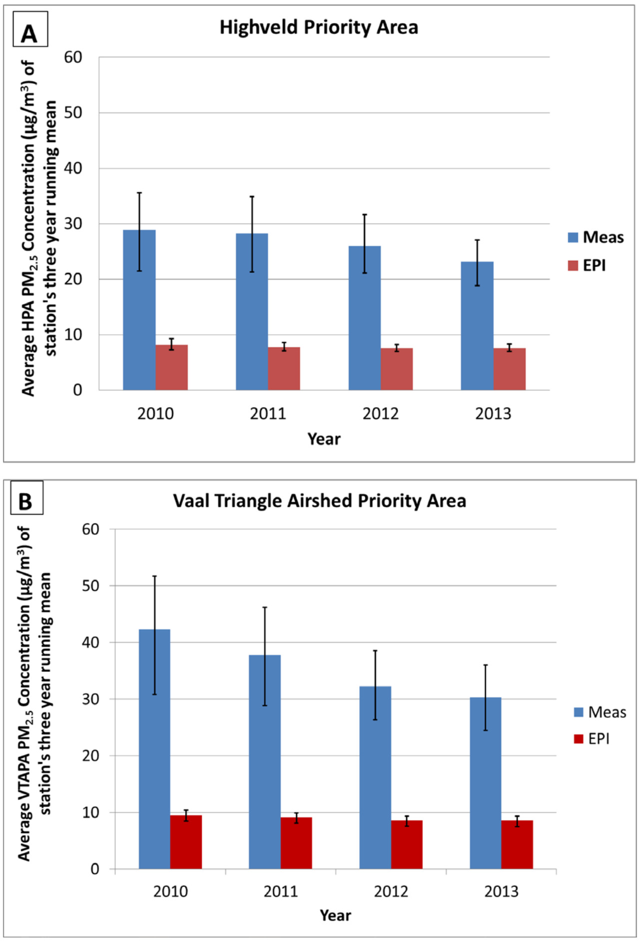

Figure 6: *Average $PM_{2.5}$ concentration of (A) the Highveld Priority Area and (B) the Vaal Triangle Airshed Priority Area stations' three-year running means from observations (blue) and EPI database (red). The bars extend from 25th to 75th percentile values of the stations' averages.*

At all sites, the EPI and the monitored data do show a decrease over the time period studied; however, due to the short length of the data set and the poor data recovery across years, the significance of this trend was not tested.

If it is assumed that this ~3 to 4 times underestimation of the EPI is valid for all of South Africa, then the resultant national PM25 values become similar to Laos, which has a rank of 172 for PM25 (out of 180). This assumption is a simplification; however, it provides a point of comparison of how such underestimation in PM25 could impact South Africa's score and assessment of the quality of the air.

The method to derive the EPI input PM2.5 data was also incorporated into the method used in the Global Burden of Disease (Burnett et al., 2014; Brauer et al., 2012). The methods are not the same, however, as Brauer et al. (2012) did use multiple data sources, including ground-based data. The underestimation of ground-level PM2.5 does still occur in the Brauer et al. (2012) dataset (Supplementary Material Table S1). Thus, it is likely that the health impacts attributable to PM in such studies are underestimated; and further research is required to refine those estimates.

Conclusion

The EPI uses indicators at a national level, as it is a comparison of 180 countries across the globe. For air quality management in South Africa, such national indicators could also be useful to understand and communicate the national state of air quality. In order to identify hotspots, however, it would be necessary to spatially resolve indicators. In addition, as can be seen here, trend analyses of indicators over time are particularly useful to understand progress. Thus, for domestic purposes, indicators that can be spatially resolved and calculated over multiple years are ideal.

Potential uses and limitations of indicators in South Africa

For the indicators assessed here, the potential use and limitations are indicator-dependent.

HAP – This index has the strongest local data sources, and in addition, spatially and temporally resolved local data are available. As domestic burning impacts indoor and ambient air pollution, an indicator of this type can be useful in South Africa to track high-level progress of solid fuel use as a proxy for air pollution exposure. This analysis could be tailored to fuels and uses in South Africa (e.g. cooking and heating assessed separately). Local Stats SA data on this are available and could be used; however, in order to understand trends the same questions must be used across surveys or else Stats SA must "backcast" usage when the question changes. However, it must be noted that Stats SA data are limited to primary fuel only, and thus do not capture the fact that a large proportion of households, in particular low-income households, rely on multiple fuels. This use of multiple fuels should be included in a local indicator.

SO2GDP and SO2CAP – These provide a helpful perspective on the intensity of SO_2 emissions. However, there are no locally derived data for comprehensive national SO_2 emissions; thus there is a strong need for local, bottom-up estimates to understand how robust findings using international data are. The trend in SO2GDP looks promising; these numbers should be ground-truthed with known emission sources.

PM25 – There are no locally derived and validated products of $PM_{2.5}$ concentrations for South Africa with comprehensive spatial coverage that could be used to estimate this indicator. Thus, in order to quantify the national PM25 indicator, global products for air quality would be needed together with local gridded data of population (such as in the EPI). However, from this study, it is clear that these underestimate $PM_{2.5}$ concentrations in the two priority areas.

It is not clear why there is this underestimation, though there may be many potential reasons for error. This comparison is comparing one sampling point to a grid cell, which assumes that the sampling point is representative of the full grid cell. The sampling stations have been sited to avoid strong local sources; however there would be spatial differences in the PM concentrations across the grid cell. As emissions are not well-quantified on a national level for South Africa, there would be uncertainties in the emissions information used in GEOS-Chem simulations. In addition, the AOD–ground-level relationship is not well quantified for South Africa, and that may lead to uncertainties in deriving ground-based concentrations from satellite information (Hersey et al., 2015). Ford and Heald (2016) estimated an uncertainty of ~20% in deriving $PM_{2.5}$ burden of mortality from satellite retrieved data due to uncertainties in the AOD–ground-level relationship alone. In addition, there are a lack of freely available and continuous ambient $PM_{2.5}$ measurements in South Africa, that can be used for ground-truthing. Even this comparison is constrained to a few sites in heavily polluted areas in South Africa.

Since PM is a pollutant of concern in South Africa, indicators based on PM exposure are key to understanding and tracking air quality. Thus, there is a critical research need to develop input data for a national assessment, as well as at disaggregated spatial scales to identify hotspots and trends in such areas. This would need more continuous measurements of $PM_{2.5}$ and modelling.

Data needs and recommendations

Basing indicators on locally measured and derived data is important. However, collecting and compiling local data for national indictors is not trivial. Bottom-up emission estimates need data and input from a variety of sources at a national scale. In addition, as can be seen here, an important analysis of such data and indicators are the assessment of their trends; this requires regular data collection and analysis for emissions estimates, and continuous monitoring for ambient concentration analysis. This can be resource intensive. However, without such data and analyses, it will not be possible to fully understand the state and trends of air quality and its impacts in South Africa. A starting point may be to focus on a small number of locally important indicators where local data are missing, and work to collect the necessary information for a first bottom-up estimate. Such estimates can then be compared to international estimates and data, which can help to identify missing sources (McLinden et al., 2016) and to decrease the uncertainties in both the local and international estimates.

It is recommended to focus on developing local information for a small number of indicators that are considered key for South Africa (e.g. SO_2 and $PM_{2.5}$). These indicators would be useful to South Africa and air quality management as they do present additional information than just ambient concentrations and exceedances. However, the strength of the indicator, and its trends, are in the underlying data.

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Supplementary Material

Global gridded pollution and population estimates used in the Global Burden of Disease 2013 are available as Supporting Information from Brauer et al. (2012). These data were downloaded (Supporting Information 005) and the $PM_{2.5}$ concentrations from the VTAPA and HPA sites were extracted for 2005, 2010, 2012 and 2013.

Table S1 below highlights the annual average $PM_{2.5}$ concentrations from this database (significant figures as reported in database). The 2005 concentrations were used in Burnett et al. (2014).

Table S1: *: Ground-level annual averaged $PM_{2.5}$ concentrations (μg/m³) from Brauer et al. (2012). Significant figures are as reported in database.*

Annual average $PM_{2.5}$ concentrations (μg/m³)					
Site		**2005**	**2010**	**2012**	**2013**
HPA	Ermelo	12.91724	12.81185	12.39297092	12.18869538
	Hendrina	11.9542	12.44675	12.4082598	12.38905936
	Middelburg	12.80226	13.46134	13.17713612	13.03729226
	Secunda	14.44574	14.57748	14.65277698	14.6905712
	Witbank	14.13451	15.9503	15.78367744	15.70102002
VTAPA	Diepkloof	24.72513	26.35033	26.69545272	26.86970548
	Kliprivier	15.9039	16.79124	16.38826719	16.19042202
	Sebokeng	16.0523	17.43382	17.58054743	17.65437359
	Sharpeville	19.50312	21.43347	22.18445547	22.56975871
	Three Rivers	19.45811	21.39796	21.41572369	21.42461106
	Zamdela	14.60568	15.44814	14.81980258	14.51528373

Air quality management in Botswana

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Abstract

This paper examines air pollution situation and the history of air quality management in Botswana. The current air quality management in Botswana is still largely underpinned by the Atmospheric Pollution Prevention Act of 1971, supplemented by the more recently enacted legislations such as the Environmental Impact Assessment (EIA) Act of 2010 and the Ambient Air Quality - Limits for Common Pollutants of 2012 published by the Botswana Bureau of Standards. Though commendable efforts have been made toward legislating against air and other forms of pollution, these have not yielded expected results in view of the prevailing levels of air pollutants like sulphur dioxide and fine particulate matters in the country's atmospheric environment. Legislation as a sole measure may not be effective in tackling this challenge. Rather, government should also address some root-causes of the problem by making policies and programmes that will reduce unemployment and increase the earning capacity of citizenry. This will, among other things, effectively check poverty-induced biomass burning in the country. The paper looks at some other challenges of air pollution management and suggestions are made to tackle the identified problems.

Keywords

Air pollutants, atmosphere, environment, carbon monoxide, mining, sulphur dioxide, nitrogen dioxide

Introduction

The environment refers to the totality of all the conditions that affect living organisms, including humans, in their habitat (Santra 2013; Girard 2014). Air is a component part of the environment that plays important life-sustaining roles, but in spite of this, it is still constantly subjected to pollution abuse. A report released by the World Health Organization (WHO) indicated that in 2012, about one in eight of global deaths was attributable to exposure to air pollution; this constituted a total of around 7 million deaths (WHO 2014). The importance of adequate air quality management cannot therefore, be over-emphasized. The increasing rate of urbanisation without the proportional infrastructural development has worsened air pollution situation in Africa (Baumbach et al. 1995; Eliasson et al. 2009). Sub-Sahara African countries, of which Botswana is one, is especially prone to soil-derived particulate matter pollution because it is largely a dry continent.

Air pollution in Botswana

Botswana is a landlocked country with an approximate area of 582,000 km^2. It is located in the centre of southern Africa with geographic coordinates of 22 00 S, 24 00 E. Census figures showed that the population of Botswana in 2011 was 2,024,904; this figure was projected to rise to 2,230,905 in 2016 (Botswana Central Statistics Office 2016). Botswana climate is semi-arid with warm winters and hot summers. The land terrain is predominantly flat to gently rolling tableland with Kalahari Desert in the southwest. The country experiences periodic droughts and August winds blow from the west, carrying sand and dust across the country. The country is faced with natural and anthropogenic environmental issues including drought, overgrazing, desertification and limited freshwater resources. Mean monthly temperatures as high as 32ºC to 35ºC are recorded in the summer months of October to January (Shaikh et al. 2006; Shaikh et al. 2006; Eliasson et al. 2009). These invariably contribute to air pollution problems in the country. Outdoor and indoor air pollution problems in the country are brought about by biomass burning, vehicular emissions, smelting activities, and population growth (Jayaratne and Verma 2001; Shaikh et al. 2006; Eliasson et al. 2009; Verma et al. 2010).

Botswana has continued to witness steady technological and population growth in recent years. Citing figures released by the Central Statistics Office in 2004, Shaikh et al. (2006) indicated that the country witnessed an increase in maintained roads from 8,000 km in 1988 to 11,000 km in 2002, while the number of vehicles increased from 65,00 to 163,000 in the same period. Meanwhile, latest figures released by the same Central Statistics Office and accessed in 2016, showed that government-maintained road network increased from the 11,000 km of 2002, to 18,507 km in 2014; which corresponds to a 7,507 km (68 %) increase. Moreover, the number of visitors that entered the country increased from 1, 200,000 in 1998 to 1,800,000 in 2002. Latest figures put number of visitors at 2,082,521 in 2014. Such human and vehicular increases must have resulted in increased fuel usage and its attendant emissions.

Jayaratne and Verma (2001) carried out a study to investigate the impact of biomass burning on the environment of Gaborone, the capital city of Botswana, using two automatic laser scattering particle counters. The size range of the particles monitored was between 0.1 μm and 5.0 μm. The mean daily particle concentrations were found to vary from about 200 particles cm^{-3} on clear visibility days during the summer to a high of over 9000 particles cm-3 on cold winter evenings. The results also showed that the size and concentrations of aerosols were consistently higher in the highly populated areas relative to low density locations. They stated that due to the absence of proper legal restrictions, majority of the inhabitants use firewood for cooking and heating purposes. In many homes, logs of wood are used for indoor heating purposes during winter, leading to a pall of smoke hanging over the city in the evenings, with a marked influence on atmospheric visibility. Follow-up studies including those of Verma and Thomas (2007); and Verma et al. (2010) have reported increasing atmospheric concentrations of aerosol particles, CO, and particulate matter of size range of 0.3-5.0 μm especially in the low income residential areas.

In addition to biomass burning and vehicular emission, a major threatening source of particulate matter air pollution in Botswana is the mining industry. Ekosse et al. (2004) noted that the growth in mining activities in Botswana may have generated corresponding increase in particulate matter. One identified major site where mining activities pose environmental contamination challenge is the Selebi Phikwe mine area (Ekosse et al. 2004). The town of Selebi Phikwe was established in the early 1960s following the onset of copper-nickel mining activities. The first official activities related to the discovery of the Selebi Phikwe mineral deposits was in 1959, when surface prospecting started over an area of about 67,000 square kilometers. Geochemical exploration techniques were used to discover the Selebi deposit in 1963 and this gave an impetus to the commencement of robust mining activities in 1970. A large proportion (26 %) of the country's labour force, dominated mainly by males, is engaged in mining of Ni-Cu (Ekosse et al. 2006). However, over the past years, there has been growing concern over environmental pollution threat posed by mining activities in the town. Ekosse et al. 2004 carried out a chemical and mineralogical characterization of particulate matter (PM) at the Selebi Phikwe Ni-Cu area in Botswana. They reported that the air in the mining area was polluted by heavy metals including cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), nickel (Ni), selenium (Se), and zinc (Zn). The results of Ekosse et al. 2004 study were also indicative of traces of very fine quartz (SiO_2), pyrrhotite ($Fe1_{-x}S$), chalcopyrite ($CuFeS_2$), albite ($NaAlSi_3O_8$) and djurleite ($Cu_{31}S_{16}$). A consortium of the Institute of Environmental Management and Assessment (IEMA) carried out an Environmental Impact Assessment (EIA) of Selebi Phikwe mining area. They reported atmospheric sulphur dioxide (SO_2) concentrations of up to 100 $\mu g/m^3$ in the mining complex as against the critical level of 20 $\mu g/m^3$ set by the European Union. The IEMA consortium found a convincing correlation between the concentration of SO_2 in the air with the apparent plant growth reduction and foliar damage in the area (IEMA 2012).

Earlier, Ekose (2005) investigated the general health status of residents of Selebi Phikwe. Data generated revealed that the most frequent common health complaints in the area included frequent coughing, headaches, influenza/common colds and chest pains. These are respiratory tract related problems, suspected to be linked to the effects of air pollution caused by the emission of SO_2 from mining and smelting activities.

Criteria pollutants of concern in Botswana

Criteria pollutants are a set of air pollutants that are considered harmful to health and the environment, and that can cause property damage. They are typically emitted from many sources including industry, mining processes, transportation, agriculture, and electricity generation. The six criteria air contaminants that were the first set of pollutants recognized by the United States (US) Environmental Protection Agency (EPA) are sulphur dioxide (SO_2), particulate matter (PM), ozone (O_3), carbon monoxide (CO), lead (Pb), and nitrogen dioxide (NO_2) (Office of Air Quality Planning and Standard, OAQPS 2013). In Botswana, some of these criteria pollutants and their environmental and health effects have been reported. These include sulphur dioxide (SO_2), particulate matter (PM), carbon monoxide (CO), and nitrogen dioxide (Jayaratne and Verma, 2001; Ekose et al. 2004; Ekosse 2005; Ekosse et al. 2006; Shaikh et al., 2006; Eliasson et al., 2009; Verma et al. 2010). For instance, Ekosse 2005; Ekosse et al. 2006 associated some respiratory health problems identified among the residents of Selebi Phikwe to particulate emissions from mining activities in the region.

Though, many authors have, in the past, identified the sources of CO pollution in Botswana viz: vehicular emissions and biomass burning, especially among the low income group households (Jayaratne and Verma 2001; Verma et al. 2010), one potential source of CO pollution in Botswana that might not have attracted attention is emission from cattle and sheep. Methane (CH_4) is produced in the stomachs of ruminants and intestine of termites. As cattle digest food, methane is produced in their intestines. The methane enters the cow's bloodstream; and when the blood gets to the lungs, the methane is released and exhaled in the normal breathing process. Oxygen in the atmosphere subsequently oxidises the exhaled methane to CO via the equation: $2\,CH_4 + 3\,O_2 \rightarrow 2\,CO + 4\,H_2O$ (Girard 2014).

History of air quality management in Botswana

There has been very little development in air quality legislation in Botswana. The Atmospheric Pollution Prevention Act which came into effect from 14th May, 1971 was promulgated to prevent the pollution of the atmosphere through emissions from industrial processes. The act empowers the Air Pollution Control Officer, appointed by the minister, to sanction any unauthorised person who carries out an industrial process capable of causing or involving the emission, into the atmosphere, of objectionable matter within a controlled area. The penalty for any convicted person under the Act ranges from a fine of P500-1000 or a prison term of 6-12 months or both, depending on whether it is a first or second conviction.

The Department of Sanitation and Waste Management was established in April, 1999 under the provisions of the Waste Management Act, 1998. Prior to this, the government developed the Botswana's Strategy on Waste Management. The Department of Sanitation and Waste Management was merged with the Air Control Division of Department of Mines in 2005, with a responsibility of implementing the Atmospheric Pollution Prevention Act, 1971. The merger gave rise to the Department of Waste Management and Pollution Control. The Department of Waste Management and Pollution Control formulates and provides policy direction and leadership to all issues pertaining to waste management, while the implementation of the policies is done by the local authorities.

The Botswana Environmental Impact Assessment Act was passed in 2005, thus making Environmental Impact Assessment (EIA) mandatory for specified projects. The EIA Act, 2005 defines the Department of Environment and Conservation as the competent authority that is responsible for administering and controlling EIA activities in Botswana. This department was renamed as the Department of Environmental Affairs (DEA) and the functions previously assigned to the National Conservation Strategy Agency (NCSA) relating to EIA in the country were transferred to DEA.

The Environmental Assessment Act, 2010 passed by the National Assembly on the 12th April, 2011 and gazetted in June, 2011, is a consolidation of that of 2005. The Act provides for EIA to be used to assess the potential effects of planned developmental activities with a view to determining and providing mitigation measures for any significant adverse effects on the environment. The Act also provides for monitoring and evaluation of the environmental impacts of implemented activities. The Act stipulates sanctions ranging from a fine of P100,000 or a prison term not exceeding 5 years or both for anyone who undertakes a developmental activity without undergoing necessary processes as put in place by the Act. Moreover, such a convicted person shall rehabilitate the area affected by the adverse environmental impact of the implemented activities. Failure to comply will attract a further fine of P1,000,000 or a term of imprisonment not exceeding 15 years, or both.

The Botswana Bureau of Standards published Ambient Air Quality – Limits for Common Pollutants (BOS 498:2012). This Standard specifies limit values (Table 1) for common air pollutants to ensure that the negative effects of such pollutants on human health and the environment are prevented or reduced.

Limit values for common air pollutants in Botswana

Pollutant	Limit value (μg/m³)	Average period
Sulphur dioxide (SO_2)	350 120	1 hour 24 hours
Nitrogen dioxide (NO_2)	200 40	1 hour 1 year
Carbon monoxide (CO)	30,000 10,000	1 hour 8 hours
Particulate matter (PM_{10})	200 100	Monthly 1 year
Ozone (O_3)	120	8 hours
Lead (Pb)	0.5	1 year
Benzene (C_6H_6)	5.0	1 year

Source: Botswana Bureau of Standards (2012)

The Botswana limit values for common air pollutants as presented in the table above compares favourably with the limits in South Africa, a neighbouring country, except for PM_{10} one year limit value which is 100 % higher the South African value of 50 μg/m³ (South African National Standard, 2011). In spite of this, the Botswana government may still have to consider a downward review of some these pollutants, especially SO_2. This opinion is hinged on the earlier mentioned IEMA Environmental Impact Assessment of Selebi Phikwe mining area which found a correlation between the 100 μg/m³ SO_2 atmospheric concentration with the prevalent plant growth reduction and foliar damage in the area (IEMA 2012).

Challenges facing air pollution management in Botswana

Like in many other developing countries, air pollution management in Botswana is faced with several challenges, some of which have already been mentioned earlier in this paper. These challenges include increasing vehicle numbers and road networks (Shaikh et al. 2006), biomass burning (Jayaratne and Verma 2001; Verma et al. 2010), growing mining and smelting activities (Ekosse et al. 2004; Ekosse et al. 2006), inadequate data to monitor and appraise pollution levels, lack of cohesive air quality policies, and weak or no legal restrictions (Jayaratne and Verma 2001). The measures put in place to manage air quality; including the Atmospheric Pollution Prevention Act of 1971, the related but more recent Environmental Impact Assessment Acts of 2005 and 2010, and the Ambient Air Quality - Limits for Common Pollutants of 2012 published by the Botswana Bureau of Standards might not have yielded expected results in view of the prevailing levels of air pollutants like sulphur dioxide and fine particulate matters in the country's atmospheric environment. This conclusion is partly based on published air quality monitoring studies (Jayaratne and Verma 2001; Verma and Thomas 2005, 2007), some of which are outdated by a couple of recent legislations in the country. There is the need for regular empirical data to allow for proper evaluation of the policies and legislations put in place to combat air pollution in the country.

The future of air quality management in Botswana and ways forward

Air quality management in Botswana requires a holistic evaluation and review to bring about significant reduction in the level of atmospheric pollution in the country. Air pollution is already taking its toll on the health and, by extension, the economy of residents, especially around Selebi Phikwe Ni-Cu plant and in the highly populated areas where the level of pollutants is high (Ekosse, 2005; Ekosse et al. 2006). Apart from strengthening existing laws on pollution prevention, effective enforcement measures should be put in place. Some of the challenges facing air pollution management in Botswana and measures that government can adopt or put in place to mitigate them are enumerated hereunder.

Increasing vehicle numbers and road network

To reduce vehicular emissions to the atmosphere, government should be more concerned in investing in quality public transport system. This will discourage the use of personal vehicles and subsequently bring about a reduction in the average number of vehicles on the roads. Importation and use of vehicles should be limited to new and fuel efficient ones. The legislation that has been put in place to set emission limits for automobile, industrial and other engines should be strengthened to ensure compliance. The use of bio-fuels which are environment friendly should be encouraged.

Biomass burning

The prevalent use of firewood, cow dung, plastic bags, and Chibuku cartons for cooking and heating purposes is fuelled by poverty and inadequate legislation (Jayaratne and Verma 2001; Verma et al. 2010). Legislation as a sole measure cannot be effective in tackling this challenge. Rather, government should address the root cause of the problem by making policies and programmes that will reduce unemployment and increase the earning capacity of citizenry. This can then be complemented by mass enlightenment and legislation. In the interim, government should find ways of making liquefied petroleum gas (LPG) and electricity affordable to the masses, probably by subsidizing the costs of these products. Electricity and LPG are more efficient and environment friendly alternatives to biomass fuels. Uncontrolled burning of wastes should be tackled by the local authorities.

Growing mining and smelting activities

The Selebi Phikwe Ni-Cu mine area is one of the most reported sources of air pollution in Botswana (Ekosse 2004; Ekosse et al. 2004, 2006). In view of the reported and potential health and environmental consequences posed by the mining plant, government and other stakeholders should work in synergy to curtail atmospheric pollutants emanating from the plant. It has been noted that a whopping 26% of the country's labour force, dominated mainly by males, is engaged in mining of Ni-Cu. Steps should therefore be taken by government and relevant bodies to reduce the over-reliance on mining, by diversifying the economy of the country and of Selebi Phikwe. Government should set sustainable emission standards for mining activities, and more importantly, ensure compliance. The huge SO_2 generated in the mining process can be captured and channelled to other productive uses such as manufacture of fertilizers and reagents like H_2SO_4. It may not be out of place for government to consider the idea of resettling the residents of Selebi Phikwe. By so doing, Selebi Phikwe will become a dedicated area for mining.

Inadequate data to monitor and appraise pollution levels

It has been observed that urban cities in developing countries are likely to have fine particulate matter concentrations up to 10-fold higher than the US National Ambient Air Quality Standards. Meanwhile, proper assessment of air pollution in these countries is difficult because of lack of cohesive air quality policies, poor environmental monitoring, and paucity of disease surveillance data (Shah et al. 2013). These observations capture the situation in Botswana, where environmental monitoring is weak and data are not available for regular evaluation of air quality. Government, stakeholders, and policy makers should set reference threshold limits values for ambient air quality for pollutants in the country. In addition, a body should be designated to monitor air quality in the country and its report should be published yearly to allow for evaluation.

The adverse effects of pollution, especially atmospheric, are now known not to be limited to the immediate locality where pollutant level is high (Dada et al. 2016). Air pollution is therefore better tackled not in isolation, but in collaboration with other neighbouring countries. Air quality monitoring data and policies in Botswana should be compared and shared with neighbouring countries – South Africa, Namibia and others.

Conclusion

Efforts to monitor air quality and control atmospheric pollutants in Botswana have not yielded expected results in view of the prevailing high levels of aerosol particles and associated compounds in the country's environment. The air pollution problem is fuelled by vehicular emissions, poverty-induced biomass burning, and mining activities among others. Since the potential adverse effects of these air pollutants on the citizens and environment may be too grievous to neglect, government and stakeholders should, as a matter of urgency, take proactive and holistic steps to tackle the identified causative problems and ensure a cleaner atmosphere. Legislation as a sole measure cannot be effective in tackling this challenge. Rather, government should address the root cause of the problem by making policies and programmes that will reduce unemployment and increase the earning capacity of citizenry. This will effectively check poverty-induced biomass burning in the country. Failure to do these may amount to a time bomb, going by the pollution-associated health challenges already identified among the citizens.

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Uncertainty of dustfall monitoring results

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Abstract

Fugitive dust has the ability to cause a nuisance and pollute the ambient environment, particularly from human activities including construction and industrial sites and mining operations. As such, dustfall monitoring has occurred for many decades in South Africa; little has been published on the repeatability, uncertainty, accuracy and precision of dustfall monitoring. Repeatability assesses the consistency associated with the results of a particular measurement under the same conditions; the consistency of the laboratory is assessed to determine the uncertainty associated with dustfall monitoring conducted by the laboratory. The aim of this study was to improve the understanding of the uncertainty in dustfall monitoring; thereby improving the confidence in dustfall monitoring. Uncertainty of dustfall monitoring was assessed through a 12-month study of 12 sites that were located on the boundary of the study area. Each site contained a directional dustfall sampler, which was modified by removing the rotating lid, with four buckets (A, B, C and D) installed. Having four buckets on one stand allows for each bucket to be exposed to the same conditions, for the same period of time; therefore, should have equal amounts of dust deposited in these buckets. The difference in the weight (mg) of the dust recorded from each bucket at each respective site was determined using the American Society for Testing and Materials method D1739 (ASTM D1739). The variability of the dust would provide the confidence level of dustfall monitoring when reporting to clients.

Keywords

Buckets, confidence, dust, dustfall, monitoring, precise, uncertainty

Introduction

Fugitive dust is a nuisance and a source of air pollution (Datson, Hall and Birch 2012). Anthropogenic sources of fugitive dust include, but are not limited to, construction, industrial and mining activities. These sources are regulated under the National Dust Control Regulations (NDCR) of 2013 (NEMA: AQA 2013). The purpose of the NDCR is to prescribe general measures for the management and monitoring of dustfall using the American Society for Testing and Materials method D1739:1970 (ASTM D1739: 1970) or equivalent internationally approved method.

Little has been published on the repeatability, uncertainty, accuracy and precision of dustfall monitoring. The aim of this study was to improve the understanding of the uncertainty and the confidence level of dustfall monitoring using the ASTM D1739: 1970 method.

Methods

A dustfall monitoring network was established along the perimeter of a lime processing facility in Gauteng and monitored for 12 months. The network consisted of 12 directional dustfall samplers that were modified by removing the rotating lid. Each sampler contained Four buckets (A, B, C and D) with the dimensions 238 mm (height) and 175 mm (diameter). (Figure 1).

The basic premise with the four buckets per stand was to ensure that each bucket would be exposed to the same conditions and for the same period; therefore, should have equal amount of dust deposition. This assumes that dustfall rates for each of the four buckets are not impacted by the close proximity of the four buckets to each other on the stand. This is an untested limitation of this study. The difference in the weight (mg) of the dust recorded from each bucket at each respective site is observed.

Figure 1: *Converted Directional Dust Bucket Stands.*

Statistical analysis

The variability of each bucket at each site was calculated to determine the difference in the dust collected for each bucket by calculating the standard deviation for each sampler. This gave an indication of precision. Box plots for all of the sites for every month show the distribution of the data.

A margin of error for each site was calculated using the following

$$E = (t_c)\frac{\sigma}{\sqrt{n}} \qquad (1)$$

Where; E = margin of error
t = critical value for confidence level c (at 90%)
σ = standard deviation
n = amount of samples

To calculate the uncertainty of the results, the mean of each site was determined. The upper and lower limits (plus/minus 10% from the mean) was used to determine what percentage of samples were outside this band.

Thereafter, the relative standard deviation (%RSD) was calculated to compare the precision of the absolute deposition values between sites.

Results

Some of the results are presented in this section, the balance can be found in appendix A to C.

The standard deviation of 144 samples (12 sites monitored for 12 months) was calculated (Figure 2). 91% of the data points had a standard deviation below 400 mg/m^2/day, 81 % of the data points had a standard deviation below 300 mg/m^2/day, and 38% had standard deviations below 100 mg/m^2/day, this gives an indication of the range of deviation for the entire data set.

The analysis of variance for the results is presented using box plots (Figures 3 and 4). These plots (representing two of the 12 months sampled) are a visual representation of the spread of the data collected for eash site. The smaller the box plot, the lower the variance, and in this case the uncertainty.

Outliers are those data points that are statistically uncertain.

A second method of measuring the uncertainty was to plot the 90% confidence interval (Figures 5 and 6) and to determine the percentage of data points that fell outside of this interval. The majority of data points (51%) at all site fell outside of the 90% confidence level.

The third method of measuring the uncertainty was to provide a band of plus/minus 10% from the mean of the four data points and determine the number of samples lying outside of the band. This is represented graphically for sites 4 and 11 (Figures 7 and 8). 28% of the 288 results were outside the band.

Finally, the relative standard deviation is calculated to compare the precision of the absolute deposition values between sites. A high RSD value indicates a high uncertainty. The average RSD for all sites and for all months was calculated at 11.69%. Most of the sites have a low percentage RSD indicating a small spread between the points (Table 1). There are some points within the dataset that have a higher variability. The cell shading in Table 1 represent the following:

- No colour: RSD below 15%
- Light red: RSD between 15 and 20%
- Red: RSD above 20%
- Dark Red: RSD above 40%

Discussion

Standard deviation is used to show how far the data spreads from the mean. The higher the standard deviation the more spread out the data is. A low uncertainty would be represented by a standard deviation of less than ±5% of the mean. The buckets at each site were exposed to the same environments; therefore, it is expected that they should collect the same amount of dust.

The box plots are a visual way of representing the data from the sample. It shows the minimum, maximum, median, interquartile ranges and outliers. They are only able to show the outlier with the greatest or the smallest value. This is due to the small data groups (populations of 4). Therefore, when the area of the box is minimal, it indicated a closely spaced dataset, which in turn means precise data, i.e. lower uncertainty. Whereas a large area within the box represents spread data with large ranges between the results, i.e. greater uncertainty. It should be considered that the amount of dust per site would vary; therefore, only the size of the box should be taken into consideration and not its position on the y-axis of the graph.

The area in which the test was conducted has a dust standard of 1,200 mg/m^2/day (NEMA: AQA, 2013). The margin of error was calculated to see if it is possible for the value of the reading to shift around this standard. That is, if the weight was just below or above the standard, would it be possible for the actual dust deposition to be above or below the standard, respectively. This confidence interval (Figures 5 and 6) indicates that for some of the samples with readings close to the standard it is possible for the result to provide a false exceedence or false conformance to the Standard.

The ASTM D1739–98 reported a standard deviation of 18% in the recovery measurements of water insoluble dustfall from Project Threshold (ASTM D1739–98. 1998), and that there was no link found between dustfall rate and reproducibility or repeatability. Repeatability and reproducibility was not conducted in this current study; however, it is aligned with the Project Threshold study. No link between the dustfall rate and repeatability (standard deviation) was found. The RSD was used to obtain an uncertainty for the entire process whereas Project Threshold

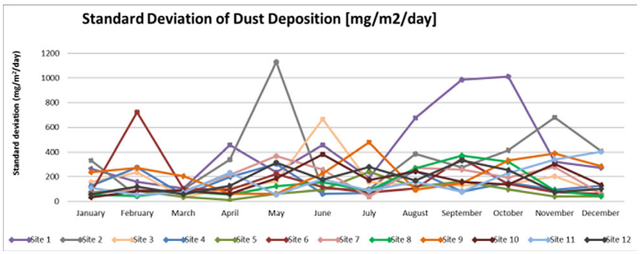

Figure 2: *Standard deviation of all the sites over 12 months.*

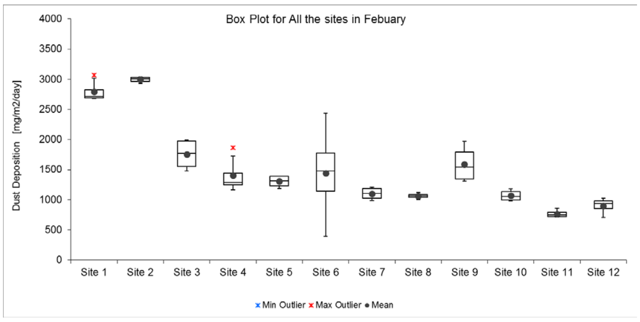

Figure 3: *Box Plot indicating the data distribution for all the sites in February.*

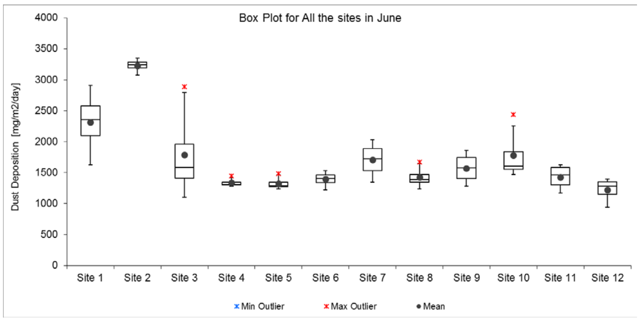

Figure 4: *Box Plot indicating the data distribution for all the sites in June.*

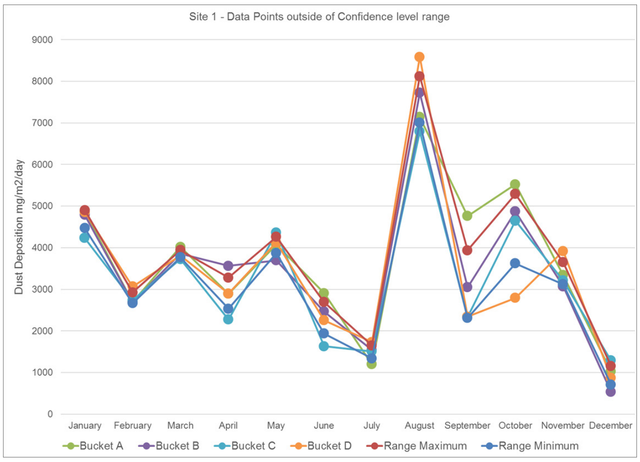

Figure 5: *Indication of data with respect to a 90% confidence interval.*

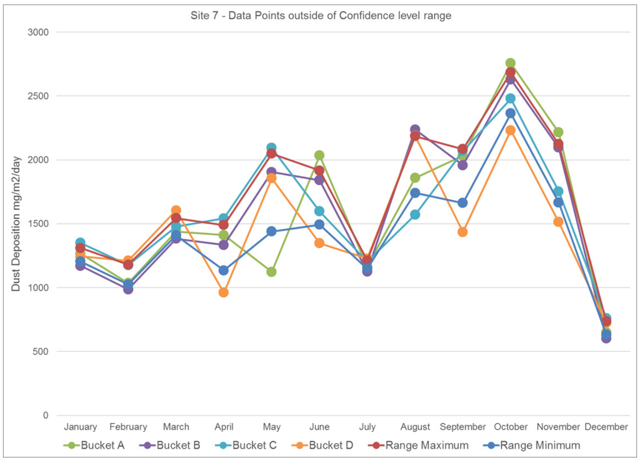

Figure 6: *Indication of data with respect to a 90% confidence interval.*

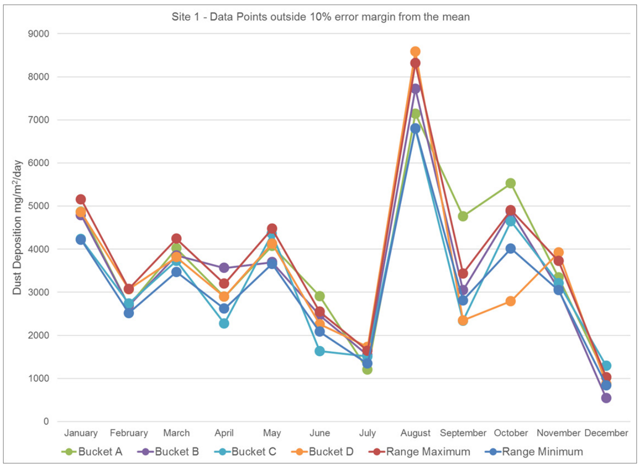

Figure 7: *Indication of data with respect to a 10% margin from the mean.*

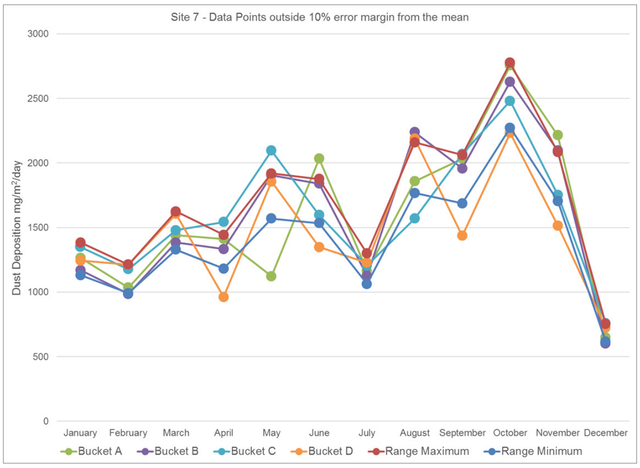

Figure 8: *Indication of data with respect to a 10% margin from the mean.*

Table 1: *The relative standard deviation*

	January	February	March	April	May	June	July	August	September	October	November	December
Site 1	5.65%	5.61%	2.75%	15.69%	5.82%	19.84%	12.77%	8.98%	31.69%	22.76%	9.53%	29.13%
Site 2	10.60%	1.53%	3.03%	13.76%	33.08%	3.11%	7.22%	14.44%	11.25%	10.28%	26.15%	22.47%
Site 3	8.10%	13.14%	1.99%	9.10%	12.22%	37.30%	10.38%	8.61%	6.53%	6.36%	12.80%	5.06%
Site 4	7.88%	19.60%	3.76%	19.86%	25.38%	4.68%	5.94%	12.64%	4.20%	6.85%	7.65%	19.05%
Site 5	5.41%	6.67%	2.89%	1.25%	4.88%	7.05%	17.68%	7.03%	10.12%	5.81%	3.09%	5.81%
Site 6	4.94%	50.16%	7.13%	5.39%	9.78%	8.15%	4.57%	7.56%	21.47%	9.11%	7.44%	9.68%
Site 7	5.09%	8.56%	5.52%	16.45%	21.19%	15.12%	3.29%	13.75%	13.67%	7.73%	14.64%	9.04%
Site 8	4.80%	4.22%	6.29%	4.66%	8.94%	10.95%	7.20%	18.79%	20.88%	16.96%	7.38%	9.66%
Site 9	14.36%	17.18%	11.56%	4.80%	4.29%	14.35%	19.44%	6.64%	7.99%	15.89%	14.39%	20.46%
Site 10	2.76%	7.84%	6.55%	4.50%	8.80%	21.61%	9.84%	16.80%	9.43%	7.78%	12.94%	20.25%
Site 11	10.49%	7.64%	5.93%	11.14%	7.03%	12.72%	4.35%	13.70%	5.17%	17.57%	24.69%	50.76%
Site 12	6.98%	13.28%	5.07%	3.97%	11.04%	14.28%	19.14%	8.91%	41.00%	9.07%	9.04%	15.69%

reported on the laboratory component of dustfall monitoring only. The current study identifies environmental conditions that have a greater contribution to the calculated uncertainty of the method.

Conclusion

The dustfall rate for each group of four samplers per site was expected to have a low variability given that they were exposed to the same conditions. However, variation in the dustfall rate indicates some level of uncertainty. The results of this study show that there is uncertainty in the results from the dustfall samplers. Although some uncertainty could be attributed to sample handling, the majority is considered to be from environmental factors.

The proximity of the four buckets on each stand could affect the flow pattern around these buckets and potentially affect the deposition into the bucket. For this study it was assumed that the effect each bucket has on the others is equal. Future work for this study will correlate the highest mass of the four buckets with the dominant wind direction.

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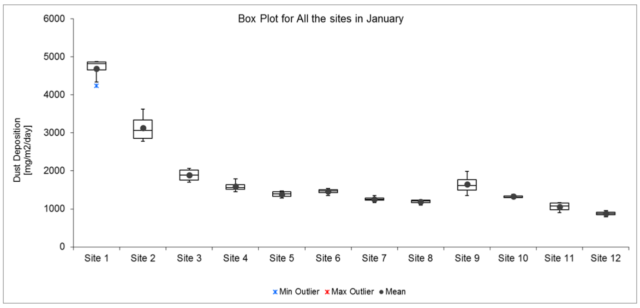
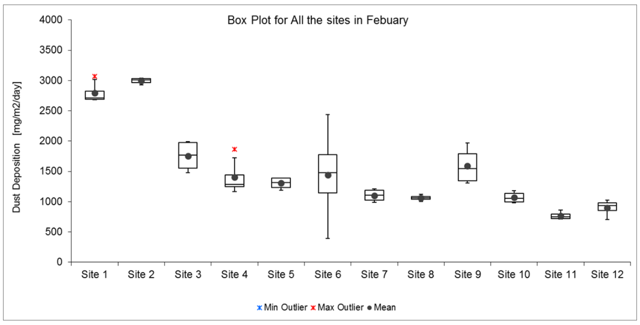
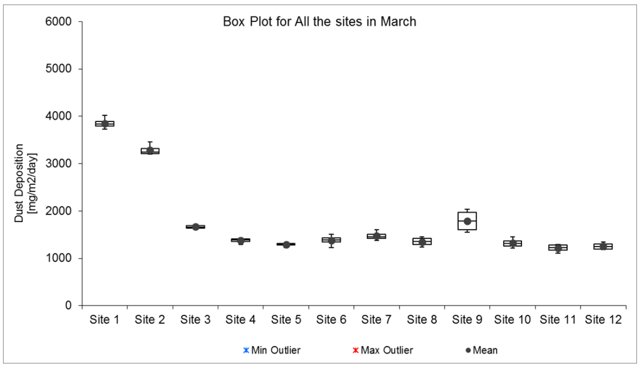
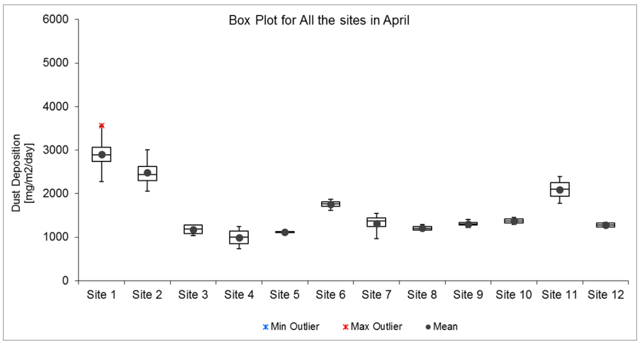
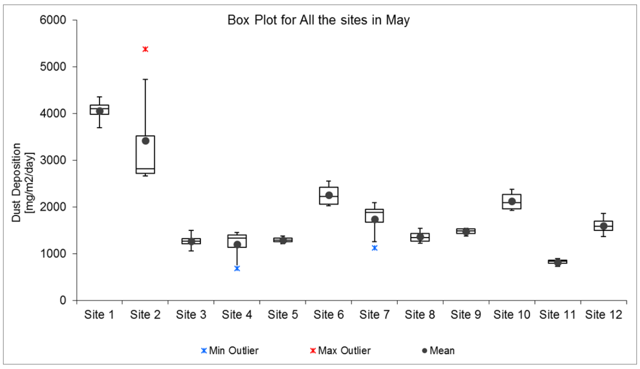
Appendix A: Monthly Box Plots

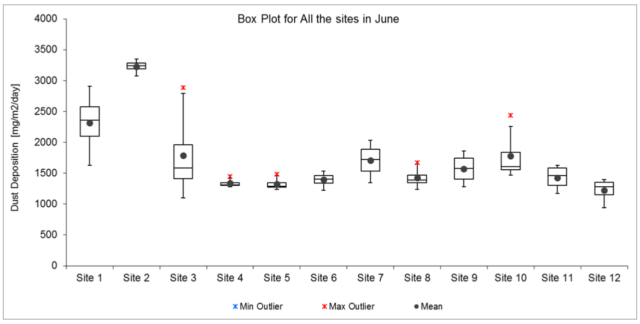


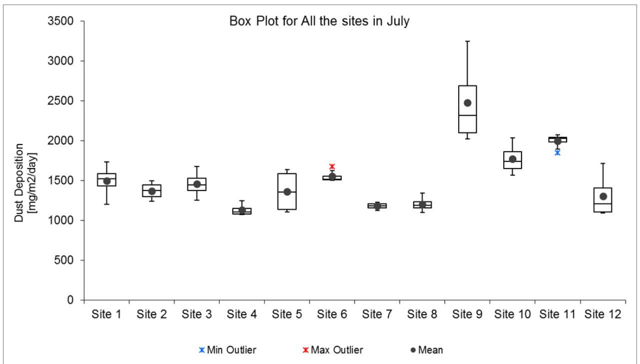


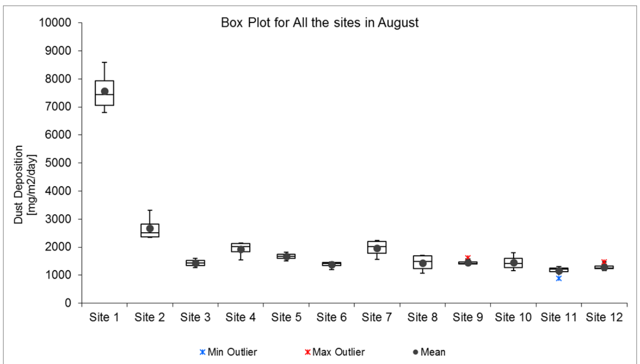


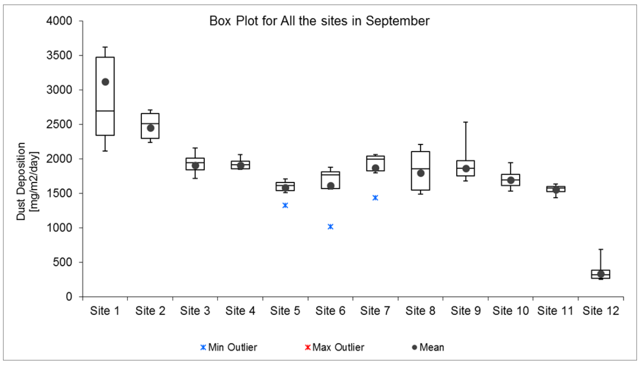

Box Plot for All the sites in April
Dust Deposition [mg/m2/day]
Site 1 Site 2 Site 3 Site 4 Site 5 Site 6 Site 7 Site 8 Site 9 Site 10 Site 11 Site 12
Min Outlier Max Outlier Mean

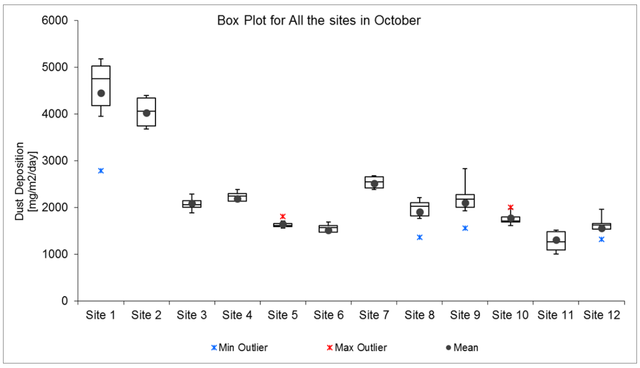

Box Plot for All the sites in May
Dust Deposition [mg/m2/day]
Site 1 Site 2 Site 3 Site 4 Site 5 Site 6 Site 7 Site 8 Site 9 Site 10 Site 11 Site 12
Min Outlier Max Outlier Mean

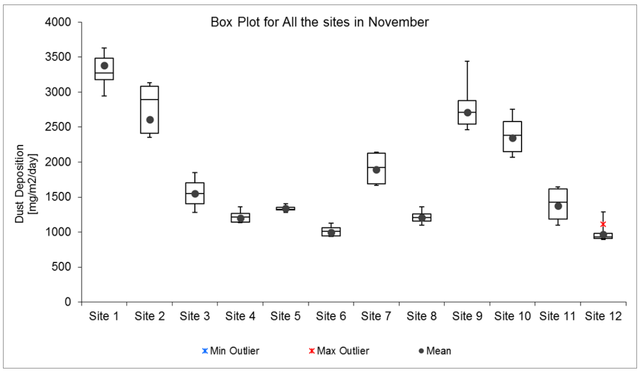

Box Plot for All the sites in June
Dust Deposition [mg/m2/day]
Site 1 Site 2 Site 3 Site 4 Site 5 Site 6 Site 7 Site 8 Site 9 Site 10 Site 11 Site 12
Min Outlier Max Outlier Mean

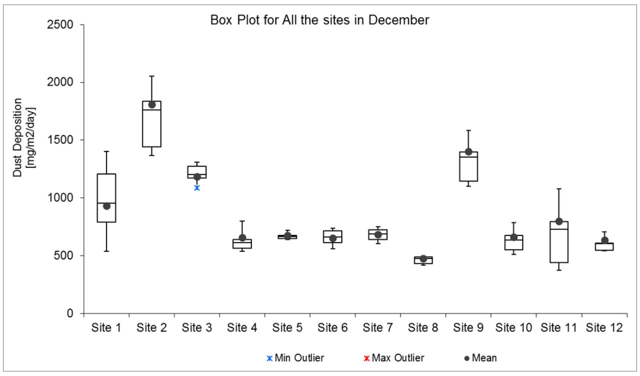

Box Plot for All the sites in July
Dust Deposition [mg/m2/day]
Site 1 Site 2 Site 3 Site 4 Site 5 Site 6 Site 7 Site 8 Site 9 Site 10 Site 11 Site 12
Min Outlier Max Outlier Mean


Box Plot for All the sites in August
Dust Deposition [mg/m2/day]
Site 1 Site 2 Site 3 Site 4 Site 5 Site 6 Site 7 Site 8 Site 9 Site 10 Site 11 Site 12
Min Outlier Max Outlier Mean

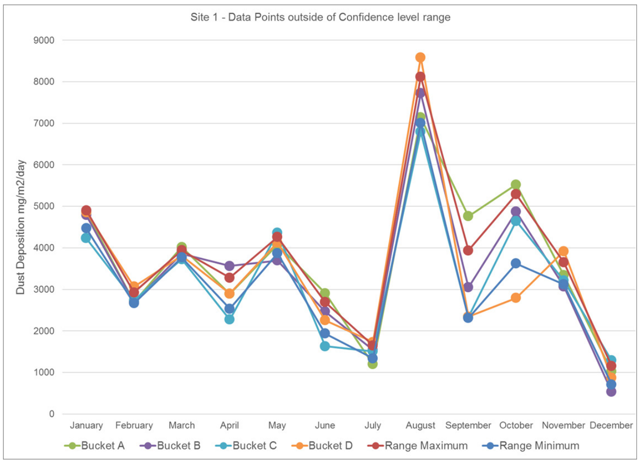

Box Plot for All the sites in September
Dust Deposition [mg/m2/day]
Site 1 Site 2 Site 3 Site 4 Site 5 Site 6 Site 7 Site 8 Site 9 Site 10 Site 11 Site 12
Min Outlier Max Outlier Mean

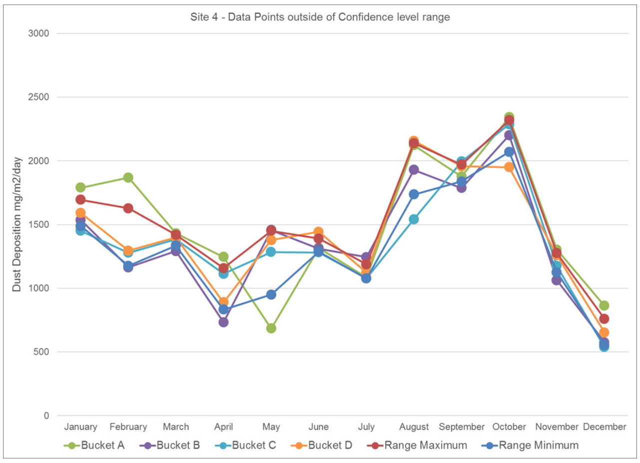

Box Plot for All the sites in October
Dust Deposition [mg/m2/day]
Site 1 Site 2 Site 3 Site 4 Site 5 Site 6 Site 7 Site 8 Site 9 Site 10 Site 11 Site 12
Min Outlier Max Outlier Mean

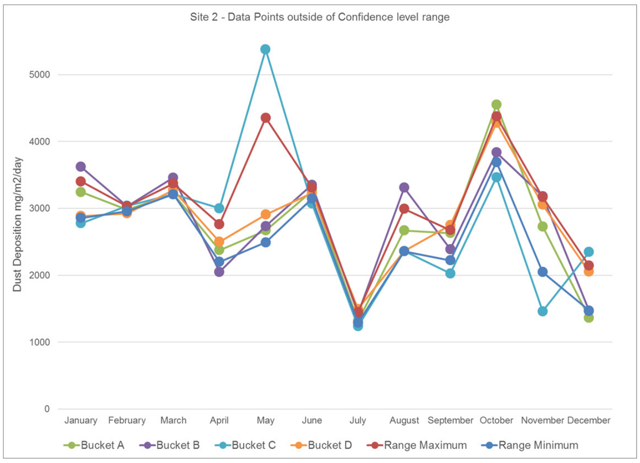

Box Plot for All the sites in November
Dust Deposition [mg/m2/day]
Site 1 Site 2 Site 3 Site 4 Site 5 Site 6 Site 7 Site 8 Site 9 Site 10 Site 11 Site 12
Min Outlier Max Outlier Mean

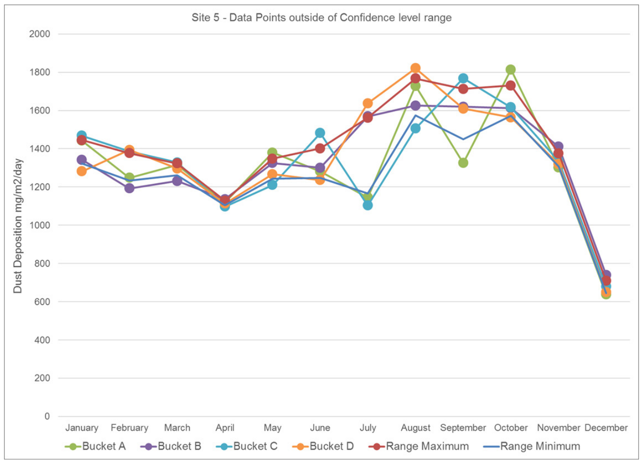

Box Plot for All the sites in December
Dust Deposition [mg/m2/day]
Site 1 Site 2 Site 3 Site 4 Site 5 Site 6 Site 7 Site 8 Site 9 Site 10 Site 11 Site 12
Min Outlier Max Outlier Mean

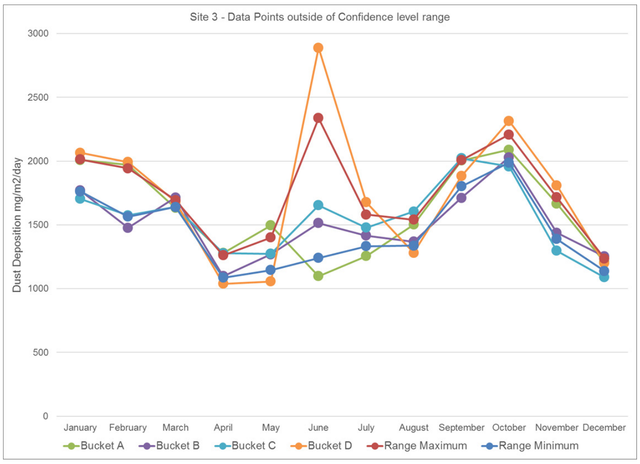
Appendix B: 90% Confidence Interval Graphs

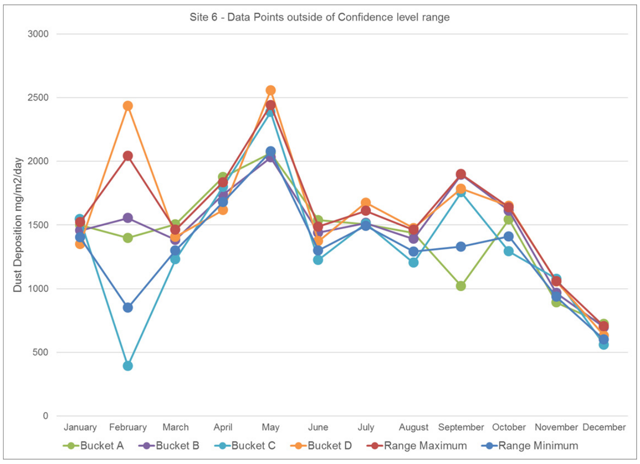


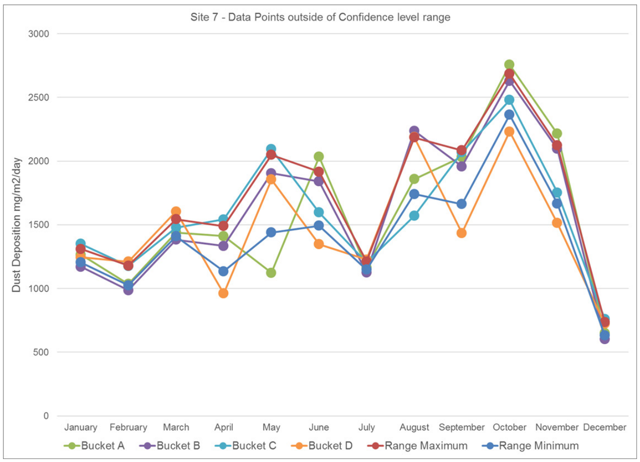


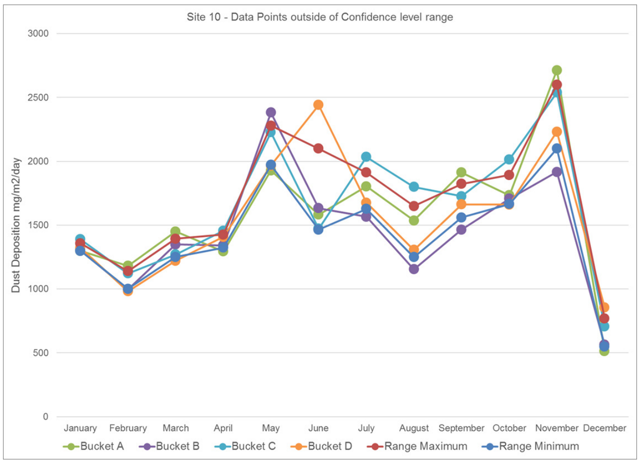


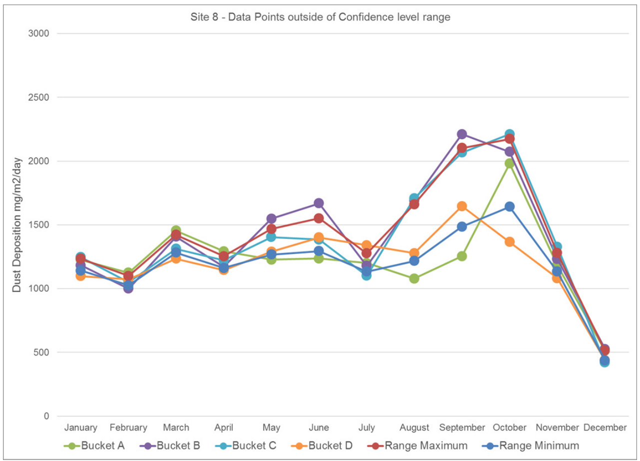


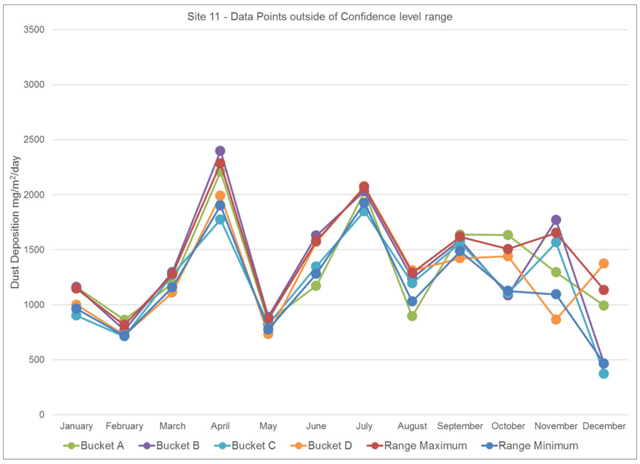


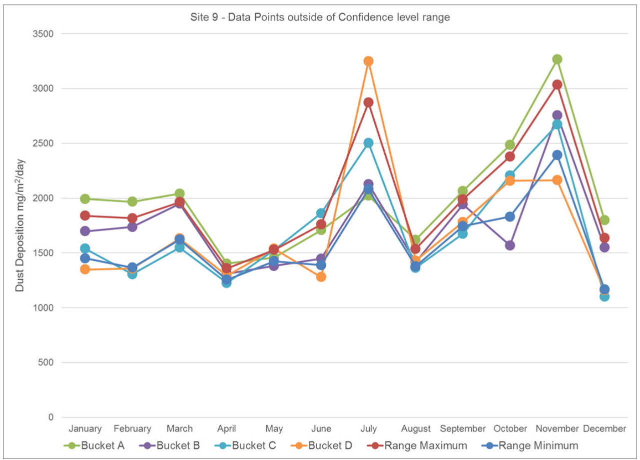


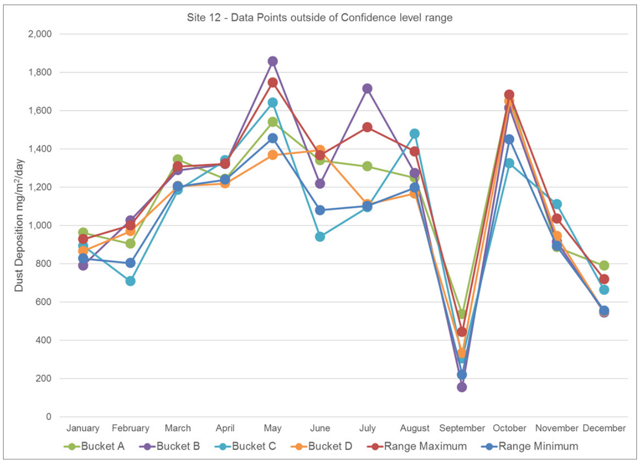

Site 7 - Data Points outside of Confidence level range
Dust Deposition mg/m2/day
3000
2500
2000
1500
1000
500
0
January February March April May June July August September October November December
Bucket A Bucket B Bucket C Bucket D Range Maximum Range Minimum


Site 10 - Data Points outside of Confidence level range
Dust Deposition mg/m2/day
3000
2500
2000
1500
1000
500
0
January February March April May June July August September October November December
Bucket A Bucket B Bucket C Bucket D Range Maximum Range Minimum

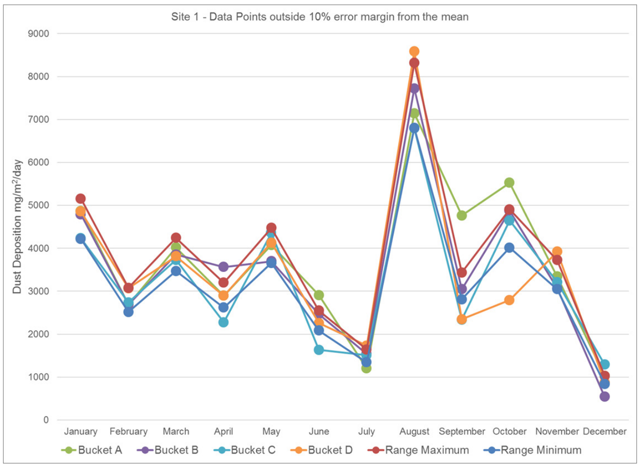

Site 8 - Data Points outside of Confidence level range
Dust Deposition mg/m2/day
3000
2500
2000
1500
1000
500
0
January February March April May June July August September October November December
Bucket A Bucket B Bucket C Bucket D Range Maximum Range Minimum

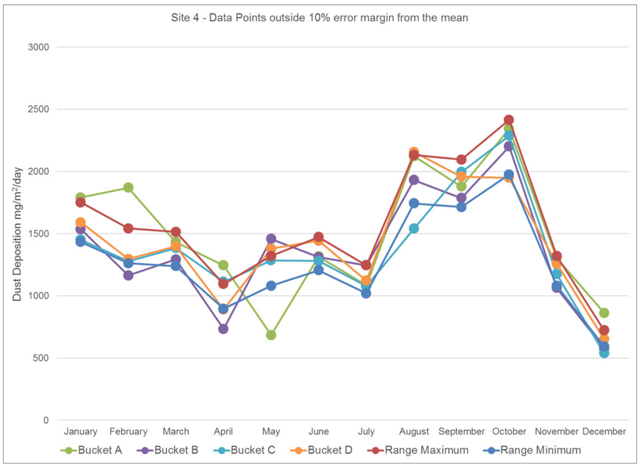

Site 11 - Data Points outside of Confidence level range
Dust Deposition mg/m²/day
3500
3000
2500
2000
1500
1000
500
0
January February March April May June July August September October November December
Bucket A Bucket B Bucket C Bucket D Range Maximum Range Minimum

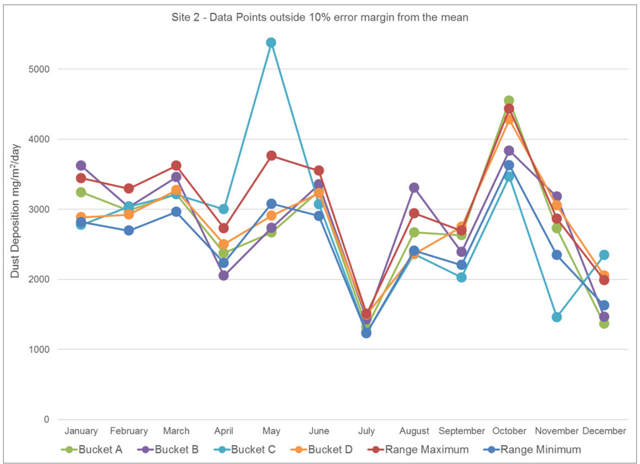

Site 9 - Data Points outside of Confidence level range
Dust Deposition mg/m²/day
3500
3000
2500
2000
1500
1000
500
0
January February March April May June July August September October November December
Bucket A Bucket B Bucket C Bucket D Range Maximum Range Minimum

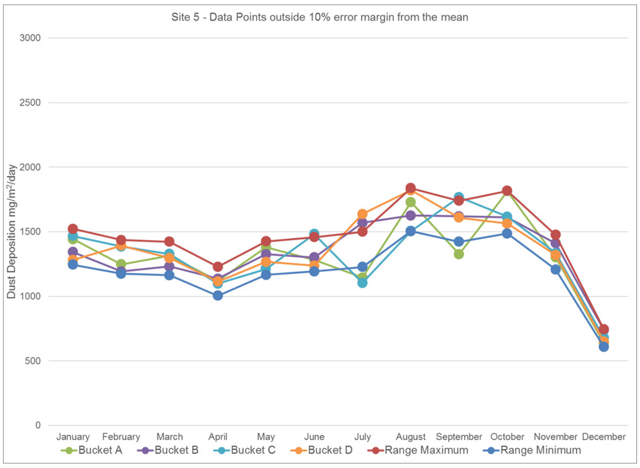

Site 12 - Data Points outside of Confidence level range
Dust Deposition mg/m²/day
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
January February March April May June July August September October November December
Bucket A Bucket B Bucket C Bucket D Range Maximum Range Minimum

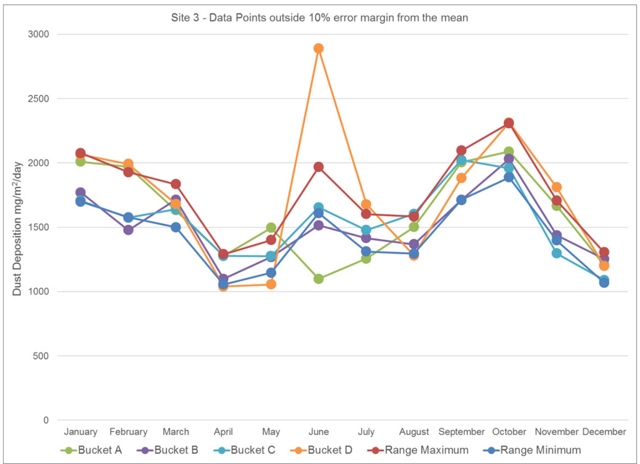
Appendix C: 10% Error Margin Graphs

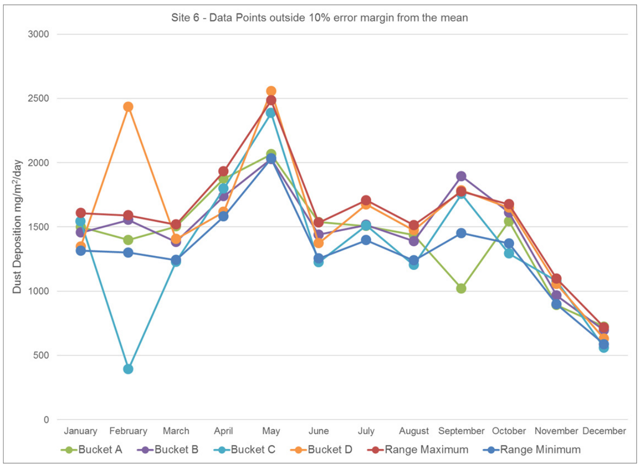


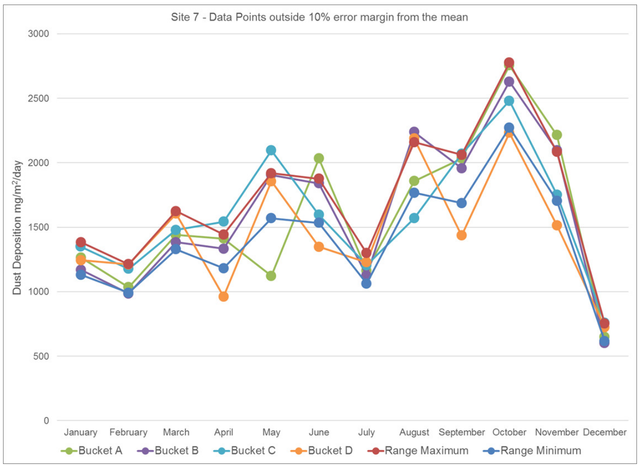


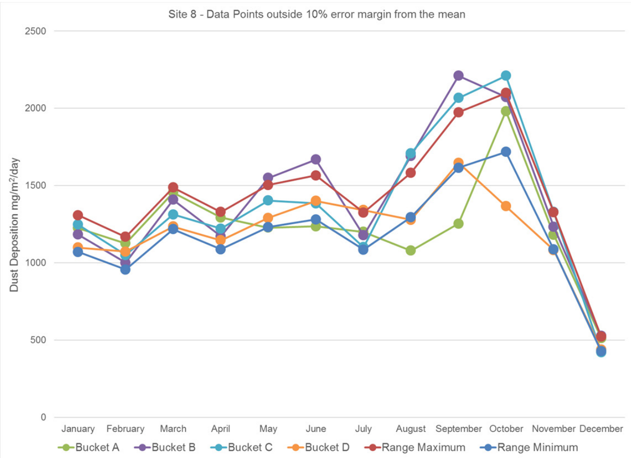


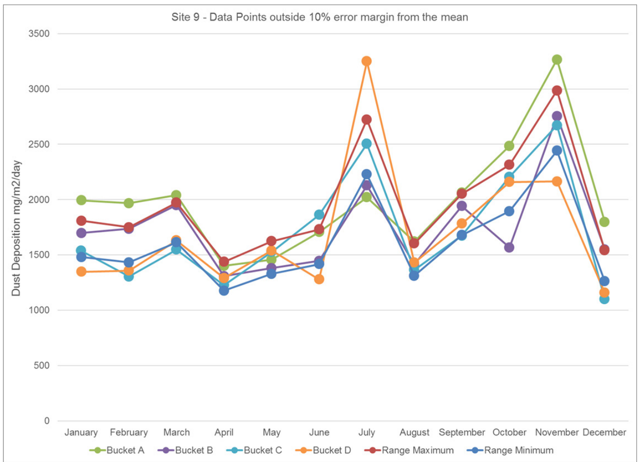


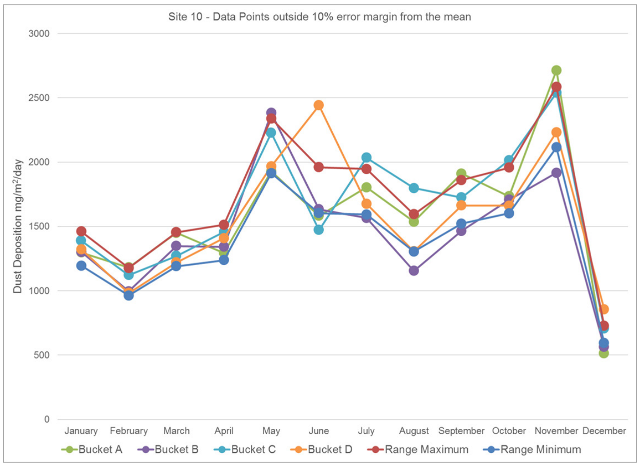


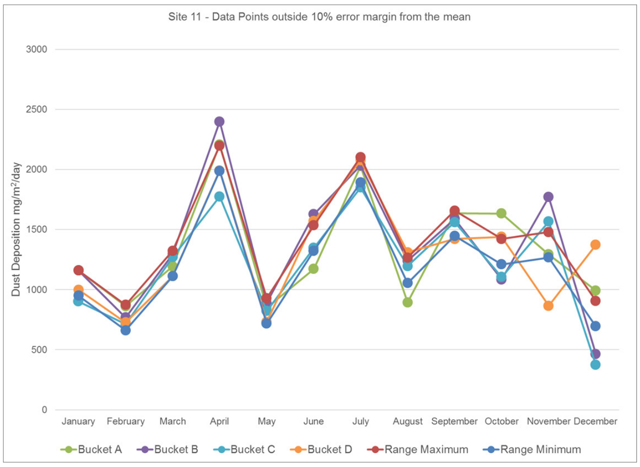


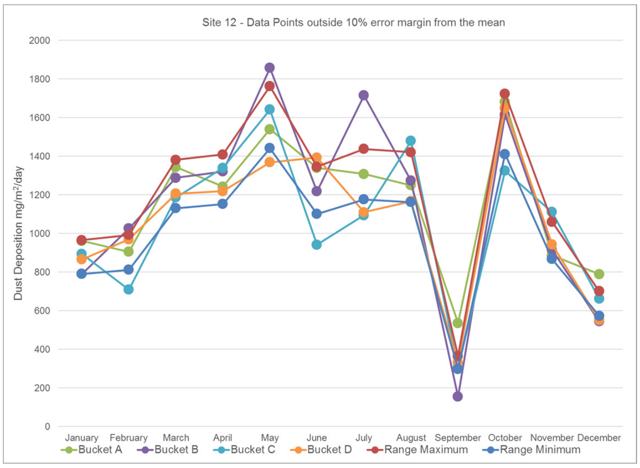

Site 7 - Data Points outside 10% error margin from the mean
Dust Deposition mg/m²/day
3000
2500
2000
1500
1000
500
0
January February March April May June July August September October November December
Bucket A
Bucket B
Bucket C
Bucket D
Range Maximum
Range Minimum


Site 8 - Data Points outside 10% error margin from the mean
Dust Deposition mg/m²/day
2500
2000
1500
1000
500
0
January February March April May June July August September October November December
Bucket A
Bucket B
Bucket C
Bucket D
Range Maximum
Range Minimum


Site 9 - Data Points outside 10% error margin from the mean
Dust Deposition mg/m2/day
3500
3000
2500
2000
1500
1000
500
0
January February March April May June July August September October November December
Bucket A
Bucket B
Bucket C
Bucket D
Range Maximum
Range Minimum


Site 10 - Data Points outside 10% error margin from the mean
Dust Deposition mg/m²/day
3000
2500
2000
1500
1000
500
0
January February March April May June July August September October November December
Bucket A
Bucket B
Bucket C
Bucket D
Range Maximum
Range Minimum


Site 11 - Data Points outside 10% error margin from the mean
Dust Deposition mg/m²/day
3000
2500
2000
1500
1000
500
0
January February March April May June July August September October November December
Bucket A
Bucket B
Bucket C
Bucket D
Range Maximum
Range Minimum


Site 12 - Data Points outside 10% error margin from the mean
Dust Deposition mg/m²/day
2000
1800
1600
1400
1200
1000
800
600
400
200
0
January February March April May June July August September October November December
Bucket A
Bucket B
Bucket C
Bucket D
Range Maximum
Range Minimum