Ambient and Indoor Particulate Matter Concentrations on the Mpumalanga Highveld

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Previous qualification (not compulsory)

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

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Graduation May 2018

24046868

Abstract

In order to better define tools for the protection of human health, the characterisation of particulate matter (PM) concentrations and the understanding of total exposure to these concentrations is critical. Many communities on the Mpumalanga Highveld in South Africa rely on coal for heating and cooking purposes. Consequently, individuals in such areas are often chronically and acutely exposed to elevated concentrations of PM, resulting in negative health impacts.

An unprecedently rich data set was used to understand the magnitude as well as the spatial and temporal variability of PM concentrations in two low-income communities on the Mpumalanga Highveld, where solid fuel is the primary source of energy for heating and cooking purposes. Ambient, indoor and personal PM concentrations of different size fractions were simultaneously considered for analysis. Personal PM- and corresponding GPS measurements were used to define and contextualise personal exposure concentrations. Data was collected between 2013 and 2016 as part of Sasol and Eskom's air quality offset pilot study sampling campaigns in KwaDela and KwaZamokuhle, respectively.

Results showed that air quality in KwaDela and KwaZamokuhle is very poor, especially so in winter months. Particulate matter concentrations were often found to be higher indoors than in the ambient environment. Ambient, indoor and personal measured PM concentrations were highly variable in space and time, as influenced by larger- and local scale meteorological conditions as well as by socio-economic factors. Peak personal exposure concentrations above the ambient air quality standards were not limited to a time of day nor to a specific micro-environment. However, high PM concentrations were most notable during peak burning times especially in and directly outside households.

This study supports the notion that data logged at a centrally located ambient air quality monitoring station should be used with caution when making compliance related decisions and when conducting epidemiological studies in these areas. Whilst ambient air quality measurements are a useful guideline to use as a basis for air quality management interventions, it is important to include measurements taken in and around a household to ensure air quality management protocols are adequate to address the poor air

quality that people breathe in low-income communities, and this particularly so on the Mpumalanga Highveld.

Keywords: Ambient air quality, indoor air quality, low-income communities, variability of particulate matter concentrations, micro-environments, total personal exposure, inhalation dose

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List of Abbreviations

AMS	Ambient Monitoring Station
Case	A *case* is a data set at an hourly average resolution that has been compiled to allow the direct comparison of ambient, indoor and personal PM concentrations as well as relevant meteorological data for a given time. A *case* typically pairs ambient and meteorological data that has been collected at the same time as indoor/-personal measurements were conducted for a specific house. As such for instance, one can compare the hourly average indoor PM_4 concentrations measured in a given hour on a given day with ambient $PM_{2.5}$ concentrations measured in that same hour on that same given day. This is useful for comparative purposes and forms the basis of analyses done in this thesis.
DALY	Disability adjusted life years
NAAQS	National Ambient Air Quality Standards
PM	Particulate Matter
PM_{10}	Particulate Matter; inhalable particles, with a diameter that is generally 10 micrometres and smaller
$PM_{2.5}$	Particulate Matter; inhalable particles, with a diameter that is generally 2.5 micrometres and smaller
PM_4	Particulate Matter; inhalable particles, with a diameter that is generally 4 micrometres and smaller
Sampling campaign	Measurements taken in a specific community for a specific season. Four sampling campaigns took place in KwaDela (winter 2013, summer 2014, winter 2014 and summer 2015). Three Sampling campaigns took place in KwaZamokuhle (spring 2015, summer 2016 and winter 2016).
µg	microgram

Acknowledgements

The final destination of this journey would not have been reached without the guidance, assistance, encouragement and support provided by many individuals, who carried me through many a rough and tough patch.

I would like to thank my supervisors for believing in me: Prof Stuart Piketh, thank you for being patient with this submission. Also, thank you for letting me come along to one of the unforgettable KwaDela sampling campaigns, which allowed me to experience first-hand how some of the data I worked with was collected. Dr Roelof Burger, thank you for your time: You truly were available at all times, especially when I visited campus. You provided me with most valuable tips on how to conquer this mountain, and I will be forever grateful for the moral support. Thank you for helping me find parking on many occasions. Dr Kristy Langerman, thank you for helping me when I was unable to see the wood for the trees! Your mentorship and guidance were priceless in this process and I am grateful that I learn from you every single day. To a few other individuals, whose names cannot be omitted from my acknowledgements:

- Alex Howard, Michael Perrie, Ryan Daniels and Christiaan Pauw for your relentless, but in the end, unfortunately futile efforts of trying to bring R closer to my heart. Alex, you were a rock of support
- Riandi Venter and Michael Swaine for providing me with GIS shapefiles for my maps
- Angelika Ronge, Margaux Giannaros for your moral support and understanding, having gone through this process yourselves
- Chantal Taylor and Neil Wilson for your objective proof-reading, tips and time
- Brigitte Language, Farina Lindeque, Ncobile Nkosi and Monray Belelie as fellow thesis submitters and NACA presenters

Lastly, and most importantly, I would like to extend my gratitude to my family for being there for me through what can only be defined as thick and thin. What would I have done without you, Marianne, Andreas and Naomi Wernecke: You carried me through what has been one of my most difficult, but most rewarding journeys. Zusammen schaffen wir alles!

This research would not have been possible without generous funding from North West University and data provided by Sasol and Eskom as part of their respective air quality offset pilot studies. Thank you to NOVA and NWU for allowing me to use the fantastic datasets collected.

Declaration

This thesis is the result of the author's original work except where acknowledged or specifically stated in the text. It is being submitted for the degree of Master of Science at North West University, Potchefstroom. This thesis has not been submitted before for any degree or examination in any other degree.

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B Wernecke

20 day of November 2017

Everyone has the right—

(a) to an environment that is not harmful to their health or wellbeing; and

(b) to have the environment protected, for the benefit of present and future generations

The Constitution of the Republic of South Africa

Chapter 1 Introduction

The literary and research context, into which this study falls, is outlined and a clear problem statement is defined. The study design is touched upon and ultimate aims and objectives of this work are introduced.

1.1 Context and problem statement

It is stipulated in Section 24 of The Constitution of the Republic of South Africa (1996), that everyone has the right to clean air that is not harmful to people's health and well-being. The air quality in many dense low-income communities in South Africa challenges this constitutional right. As has been emphasised in numerous health studies, as well as recently confirmed and published in the national "Draft Strategy to Address Air Pollution in Dense Low-Income Settlements", measured ambient pollution concentrations have shown that, within low-income communities specifically, National Ambient Air Quality Standards (NAAQS) are regularly being exceeded (South Africa, 2016). This poses a threat to human health and to the environment in those areas (Engelbrecht *et al.,* 2000; Norman *et al.,* 2007; Lim *et al.,* 2012).

In order to design and support suitable implementation strategies to prevent and reduce health risks associated with air pollution, reliable estimates of human exposure to inhalable air pollutants are necessary. Similarly, to be able to support health impact assessments and effective air quality management, it is also essential to develop a better understanding of individual exposure pathways in people's everyday lives.

Domestic burning generates a range of hazardous outdoor and indoor air pollutants. Exposure to these emissions represents a prominent cause of morbidity and mortality in developing countries, attributing to more than four (4) million premature deaths globally (Lim *et al.,* 2012; Fullerton *et al.,* 2008; Rosenthal *et al.,* 2017). People most affected, are those living in low-income communities who conduct solid fuel combustion activities to meet their primary domestic energy requirements. These communities are trapped

at the bottom of the energy ladder and make use of dirty fuels for cooking and heating, particularly in winter months (Kroon *et al.,* 2011; Yangyang *et al.,* 2015).

In South Africa, the management of criteria pollutants, which are considered to be detrimental to the health of the public and to the environment, is based primarily on set NAAQS (Table 1.1) (South Africa, 2009; South Africa, 2012b). Ambient air quality standards set thresholds for *health-harmful* pollution levels (WHO, 2016). Particulate matter (PM), specifically $PM_{2.5,}$ is an important criteria pollutant for which no low-concentration threshold exists that does not cause a discernible health effect (Jantunen *et al.,* 1998). $PM_{2.5}$ concentration levels have been found to exceed ambient air quality standards in low-income communities in South Africa (Hersey *et al.,* 2015).

Table 1.1. South African National Ambient Air Quality Standards for Particulate Matter (South Africa, 2009; South Africa, 2012b)

PM Type	Averaging Period	Concentration (µg/m³)	Allowed Frequency of Exceedance
PM_{10}	24 hours	75	4
	1 year	40	0
$PM_{2.5}$	24 hours	40	4
	1 year	20	0

Human exposure to suspended particulates in many South African low-income communities, stemming most notably from domestic burning practices, has been identified to be characterised by air quality which exceeds ambient standards by three (3) to four (4) times or more (Mdluli, 2007; Hersey *et al.,* 2015; Garland *et al.,* 2017). Exposure to such high concentrations of air pollution has been shown to increase the risk of common and serious diseases such as respiratory and cardiovascular illnesses (Scorgie & Thomas, 2006; Norman *et al.,* 2007; Lim *et al.,* 2012).

Many will argue that a compliance status with the NAAQS represents a poor proxy upon which to draw conclusions for decision making purposes (Oglesby *et al.,* 2000; Adgate *et al.,* 2002; Wilson, 2006). Exposure studies have shown that it is immensely complex to ascertain and understand the air that people breathe and are exposed to, because total individual exposure varies greatly in space and time and is difficult to define (Adgate *et al.,* 2002). Compliance with the NAAQS does not take into account the air quality in different micro-environments, such as for instance the indoor environment, where many people

spend the majority of their time (Wang *et al.,* 2015). Ambient air quality readings are widely used as a surrogate value to determine whether or not the air quality in a given area at a given time is safe to breathe (Oglesby *et al.*, 2000; Payne-Sturges *et al.,* 2004). Though an important indicator of the general state of air, it is queried whether such centrally logged measurements are an adequate means to draw health-related conclusions (Oglesby *et al.,* 2000).

1.2 Aims and objectives

This study aims to characterise PM concentrations in the ambient and the indoor environment within two low-income communities on the Mpumalanga Highveld, South Africa, namely, KwaDela and KwaZamokuhle. Coal burning activities are particularly common here, as coal mines are an almost ubiquitous source of cheap fuel used for cooking and heating activities (Stats SA, 2012b). This, along with the fact that the creation of indoor fires is a culturally entrenched phenomenon, has led to the assumption that the air quality in these communities, much like other low-income communities in the province, is characterised by concentrations that regularly exceed ambient standards (Balmer, 2007; Mdluli, 2007; Garland *et al.*, 2017). The specific research objectives of this study are to:

1. Characterise overall ambient, indoor and personal PM concentrations in KwaDela and KwaZamokuhle, Mpumalanga;
2. Determine the relationships between ambient, indoor and personal PM concentrations in KwaDela and KwaZamokuhle, Mpumalanga; and
3. Explore personal exposure to PM in KwaDela.

The results of this study ultimately help us to better understand the magnitude of ambient, indoor and personal PM concentrations that are prevalent in both settlements and how they vary in space and time. In particular, this study helps answer the question of whether what is measured in the ambient environment by a stationary monitoring site is an adequate proxy to use to represent the air that is breathed by the people in these communities.

1.3 Study Design

The bulk of the findings of this study have been based on conclusions stemming from the analysis of empirical data gathered by means of physical measurements in various locations in two low-income communities on the Mpumalanga Highveld: KwaDela and KwaZamokuhle. These findings are, where possible, supported, re-enforced and contextualised by survey data results, as collected in these same two communities. A summary of ambient, indoor and personal PM concentrations is presented to introduce the reader to what has been measured in a low-income community setting throughout the seasons of the year. These measurements are compared to existing NAAQS to draw compliance-related conclusions. Factors governing the variability of PM concentrations are considered and personal exposure to these concentrations in various micro-environments is assessed by the use of zoomed-in case-studies. Finally, statements are made drawing inferences from the results which indicate what air pollution levels in these communities are like and whether or not ambient air quality measurements in KwaDela and KwaZamokuhle could be used as surrogate values for personal exposure assessments. To cover this subject matter, this thesis is divided into the following chapters:

Chapter 1 – This introductory chapter sets the context of the research study. It also outlines the aims and objectives and the study design.

Chapter 2 – A literature review is presented in this chapter of the thesis. It outlines where this study fits into the bigger picture of research conducted in this field.

Chapter 3 – The study area is introduced in this chapter. Furthermore, the methodology used for data collection and data analysis is set out.

Chapter 4 – This chapter characterises PM concentrations within and between the low-income communities considered in this study. Spatial and temporal variability of the data is defined.

Chapter 5 – To better understand how societal parameters influence PM exposure at a household level, a two-household case-study is introduced. Traits characterising community-level PM concentrations are demonstrated at a household level. The relationship between ambient, indoor and personal PM concentrations is discussed. Finally, personal PM measurements are corresponded with personal GPS coordinates and personal exposure to PM is assessed.

Chapter 6 – Conclusions and main findings are outlined in the final chapter of this dissertation.

1.4 Presentations and publications

Selected results presented in this study have been captured and presented at the National Association for Clean Air Conference in 2015 and 2016, respectively. A paper titled "Indoor and outdoor particulate matter concentrations on the Mpumalanga Highveld - A case study" was published in the *Clean Air Journal*, 25(2):12-16 in 2015.

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The aims and objectives of this study were outlined and placed into context.
The next chapter represents a review of relevant literature.

Chapter 2 Literature Review

The research conducted in this study is contextualised by placing it into current and existing national and international literature that covers the subject matter at hand: poor air quality in poverty-stricken areas and the resulting negative health implications. Health impacts related directly to exposure to high PM concentrations are outlined. Thereafter, the topic of poor air quality in the South African context, particularly so in low-income communities on the Mpumalanga Highveld, is considered. The fact that PM concentrations in a low-income community setting are highly variable in space and time is touched upon to lead to an explanation of how high variability of PM concentrations makes it difficult to define total personal exposure. After variability of ambient, indoor and personal PM concentrations is discussed at length, the complex relationships between these concentrations is explored. Finally, the relevance of this study is explained.

2.1 Health effects of poor air quality

In 2015, over 90% of the world's population lived in areas governed by "unhealthy air" (Health Effects Institute, 2017). There is no shortage of published work that delves into the negative health effects of air pollution, which can be described as a "multifaceted mix" made up of a combination of airborne particles and gases (Brunekreef & Holgate 2002; Cohen *et al.,* 2015; Morakinyo *et al.,* 2017). Exposure to suspended pollutants has been associated with increased disease, resulting shortened lives and death (Brunekreef & Holgate 2002; Lim *et al.,* 2012). In particular, a significant correlation has been found to exist between exposure to PM air pollution, morbidity and mortality (Iwai *et al.,* 2005; Krall *et al.,* 2013). Even short-term exposure to PM contributes to acute cardiovascular and pulmonary health problems, and exposure to elevated PM levels over the long-term can reduce life expectancy (Brook *et al.,* 2010; Krall *et al.,* 2013). Data on daily mortality has indicated that, globally, 4-8% of premature deaths may occur due to the exposure to total suspended particles (TSP), especially fine particles ($PM_{2.5}$) in the ambient and indoor environment (Massey *et al.,* 2009).

Exposure to air pollution from the combustion of solid fuels has been found to be a contributory cause of several diseases in developing countries. These include acute respiratory infections and otitis media (middle ear infection), chronic pulmonary disease, lung cancer (especially from coal smoke), asthma, nasopharyngeal and laryngeal cancer, tuberculosis, prenatal conditions and low birth weight (as a result of maternal exposure), and diseases of the eye such as cataract and blindness (Ezzati & Kammen, 2002; Lozano *et al.*, 2007).

A study conducted in the rural villages of the Himalayas for instance, took into account short- and long-term exposure events and estimated the burden of disease for acute lower respiratory infection, chronic obstructive pulmonary disease and lung cancer using World Health Organisation guidelines for rural households, using fuel-wood for cooking (Pandey, 2012). It was found that, households that used fuel-wood for energy intensive activities, had disability adjusted life years (DALYs) lost and the number of deaths in these areas were found to be higher than the national average. DALYs represent a measure of the "loss of healthy life expectancy and are calculated as the sum of the years of life lost from a premature death and the years lived with disability (for example, blindness, caused by the disease diabetes)" (Health Effects Institute, 2017).

Different population groups are exposed to different PM concentration levels, due to their various lifestyles (Mehta & Shahpar, 2004). Marginalised socio-economic and demographic groups (women, young children and the elderly, for instance), are more at risk of being exposed to emissions stemming from domestic burning activities than working adults (mostly men), who spend most of their day outdoors and in their respective working environments (Ezzati & Kammen, 2002). In Nigeria, blood tests were conducted on 59 mother-child pairs that were exposed to PM emissions stemming from solid-fuel burning practices (Oluwole *et al.*, 2013). Results indicated detectable adverse effects in mothers and children who were exposed to household air pollution (Oluwole *et al.*, 2013).

In a recent global burden of disease study, where burden of disease refers to the assessment of mortality, morbidity, injuries, disabilities and other risk factors specific to that country, indoor air pollution arising from the burning of coal and wood for domestic cooking and heating was found to be the seventh (7^{th}) greatest disease risk in southern Africa, while ambient air pollution represented the 25^{th} highest disease

risk (Lim *et al.*, 2012). Estimates of the burden of disease are crucial for targeting health interventions that make a significant impact on the well-being of the population (Bradshaw *et al.*, 2003).

2.2 Exposure to particulate matter concentrations

To understand the negative health effects of coming into contact with high PM concentrations, the notion of "exposure" to air pollution has been widely discussed in literature (Jantunen, 2007; Lozano *et al.*, 2007; Fullerton *et al.*, 2008; Chowdhury *et al.*, 2013; Lin *et al.*, 2013; Umoh *et al.*, 2013; Thomas *et al.*, 2015). The concept of exposure is defined differently across studies, but general consensus expresses it as "human contact with a chemical agent or a pollutant at a visible external boundary (e.g. the skin), where the chemical concentration at the point of contact is the exposure concentration" (U.S. EPA 1992). Total exposure, which takes into account the period of time an individual comes into contact with an exposure concentration, is derived by using the equation:

$$E = \int_{t1}^{t2} \boldsymbol{C(t)dt} \qquad (1)$$

Where E is the magnitude of exposure, C(t) is the exposure concentration as a function of time and t is time, $t_2 - t_1$, representing the exposure duration (ED) (U.S. EPA 1992). Once the magnitude of exposure has been determined, an exposure assessment can qualitatively or quantitively *evaluate* the contact with the exposure concentration. In the case of exposure to air pollution, this means that an exposure assessment can describe the amount of a pollutant that is inhaled into the body of an individual, i.e. the amount of a pollutant that actually crosses the external boundary, all of which is not absorbed by the body (potential dose) (Figure 2.1).

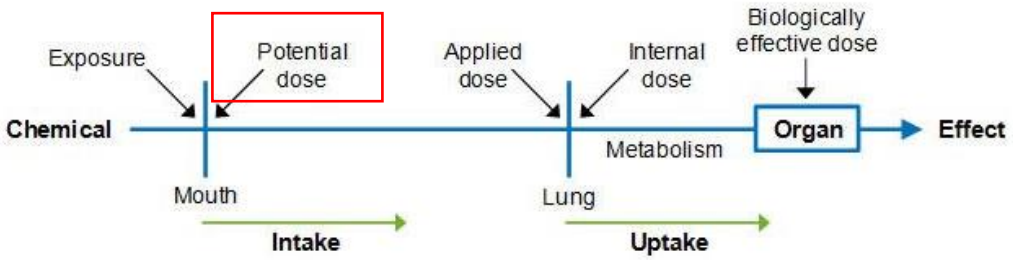

Figure 2.1. Illustration of Inhalation Route: Exposure and Dose (U.S. EPA 1992)

The general equation for potential dose for inhalation is the integration of the chemical intake rate (concentration of the pollutant in the air times the intake rate of the air, C times IR) over time (U.S. EPA1992):

$$D_{pot} = \int_{t1}^{t2} \boldsymbol{C(t)\ IR(t)dt} \qquad (2)$$

Where D_{pot} is potential dose and IR(t) is the inhalation rate of an individual. The quantity $t_2 - t_1$, as before, represents the period of time over which exposure is being examined (U.S. EPA1992).

The above methods describe how the *intake* of an exposure concentration is assessed. More detailed exposure assessments work towards defining the *uptake* of a contaminant or chemical and look at deriving the *applied dose*, the *internal dose* and finally the *biologically effective dose* of a contaminant (Figure 2.1). The determination of each of these dose types determines, with increasing level of complexity, how much an exposure concentration ultimately is taken up into the body and how it interacts with and affects organs and tissue within the body of an individual (U.S. EPA, 1992). For the purpose of this study, these dose uptake measures will not be elaborated upon, as they are not the focus of the research.

Generally, it can be said that the amount of a pollutant that enters through the upper respiratory tract of an individual and then into the lungs, is in actual fact less than what is initially breathed into the body (the potential dose) (U.S. EPA, 1992). Individuals at different ages and of different genders have different breathing rates, which determine how much of a specific pollutant is inhaled into the respiratory system and how deeply (Smith, 1993; Wilson *et al.*, 2000). Physiology, size, activity level and age are only a few of the factors that influence the breathing rates of an individual (Wilson *et al.*, 2000). The U.S. EPA has published recommended long- and short term breathing rates for adults and for children, based on the findings of relevant studies (U.S. EPA, 2011). Accordingly, long-term breathing rates for children for instance, range from 3.5 m^3/day (for ages three (3) months – one (1) year) to 16.3 m^3/day (for ages 16 - 21 years). Average breathing rates for adults (men and women combined) range from 12.2 m^3/day (for ages 81 years and older) to 16.0 m^3/day (for ages 31 to 51 years) (U.S. EPA, 2011). Short-term breathing rates are useful when activity patterns are known and are typically expressed in volume per minute (U.S. EPA, 2011). The more active an individual, the faster his/her breathing rate and the larger the volume of air that is inhaled (Chowdhury *et al.*, 2012).

A study conducted in Bangladesh to quantify indoor air pollution stemming from the use of domestic cookstoves, estimated the health effects of indoor air pollution on adult women (Chowdhury *et al.,* 2012). The inhaled dose/ potential dose of $PM_{2.5}$ exposure was ascertained by using the above equation (2). The inhalation rate used was 18 m^3/day and the exposure concentrations used represented average indoor $PM_{2.5}$ concentrations. Potential inhalation doses ranged between 4.4mg and 5.8mg of $PM_{2.5}$ per day (Chowdhury *et al.,* 2012).

It is possible to derive indirect and direct exposure concentration estimates to air pollution: Indirect estimation methods include the use of questionnaires/ time-activity diaries and measurements taken at stationary monitoring sites to ascertain lifestyle and household characteristics pertinent to relative exposure to ambient as well as indoor sources of PM. This includes the estimation of time spent in specific micro-environments and corresponding this with the average PM concentrations measured in those environments (Jones *et al.,* 2000; Mdluli, 2007). Direct methods, on the other hand, consider scientific measurements which include the concept of inhalation-based exposure assessments by using personal monitors (Abbey *et al.,* 1999). Holistic total exposure estimates would take into account a combination of both indirect and direct measurements alongside detailed personal activity patterns.

Although indirect exposure assessments may imply exposure levels by means of causation, direct personal concentration exposure measurements are considered the most accurate approximation method to use to understand total and true exposure for numerous air pollutants as indirect exposure assessments can often mask the complexities of total exposure to PM concentrations (Ezzati & Kammen, 2001; Wichmann, 2006). Total exposure, regardless of whether it is defined directly or indirectly, is a function of time spent exposed to various indoor and ambient pollution sources, may these be natural or anthropogenic in nature.

In a South African study conducted in KwaGuqa, Mpumalanga, concentration exposure to PM_4 was estimated both directly and indirectly (Mdluli, 2007). In the direct approach, exposure concentrations were determined on individuals by using a personal sampler, in the indirect approach, concentration exposure levels were measured by stationary DustTrak aerosol monitors. Population exposure to a specific pollutant fraction type was ascertained: Daily concentrations of PM_4 as well as the estimated amount of time that people spent inside their houses were used to assign population exposure to PM_4. Time-budget and time-activity patterns received from surveys were used to support the monitored data. It

was found that, for the indirect exposure assessments, exposure to the highest PM_4 concentrations was always found to be in the indoor environment. The direct exposure assessment however, showed that ambient pollution sources also contributed greatly to the total exposure of an individual.

Limitations of most pollution exposure and epidemiology studies include (i) the short time frames of most of the research, which do not account for long-term exposure and its health effects; (ii) obtaining reliable data from personal monitors (individuals can easily disrupt the measurement); (iii) the high costs and labour intensive nature of the personal measurements and finally (iv) obtaining consent from individuals to participate in the study, as this is an invasion of privacy (Brunekreef & Holgate, 2002; Wichmann, 2006).

Ambient and indoor air are a potential source of exposure to toxic airborne substances (U.S. EPA, 2011). Ambient PM sources in the low-income community context specifically, include emissions from motor vehicles and untarred roads, wind-blown dust, industries burning dirty fossil fuels, waste burning activities and domestic use of highly polluting fuel types (Mdluli, 2007; Norman *et al.,* 2007). Indoor PM concentrations are defined by a similarly wide range of sources, such as sand, clay, soil, smoke residuals from heating, cooking or smoking, cleaning agents, residues from synthetic fibres, building materials and a multitude of other materials created in the home or transported in from the outside either manually or through infiltration/ penetration (Thatcher & Layton, 1995). Studies have shown that coal burning activities related to cooking and heating activities represents one of the largest source contributors to ambient and indoor PM concentrations (Engelbrecht *et al.,* 2002).

Additionally, time of day and seasonal changes define the exposure of a person to PM in any micro-environment, because temporal and seasonal factors influence the time-activity patterns of an individual and thus determine where a person spends time (Jones *et al.,* 2000). Having noted this, it makes sense to say that total human exposure is characterised by multiple factors and that it is a concept that is not at all straight-forward to define.

2.3 Fuel use and air pollution in low-income communities

At a global level, people living in poverty stricken and low-income areas are particularly affected by high ambient and indoor air pollution levels (Health Effects Institute, 2017). This is mainly because they rely primarily on dirty, solid fuels for their energy needs, which are substantially more polluting than liquid or gaseous fuels (Smith, 2000).

In China, for example, poor air quality has increasingly become a concern, especially in the developing urban centres. It has been estimated that indoor air pollution from solid fuel use is responsible for approximately 420 000 premature deaths every year (Chen *et al.,* 2011; Lin *et al.,* 2013; Zhao *et al.,* 2015; Xu *et al.,* 2016). More than 60% of China's population lives in a rural context, where solid fuels, like coal or wood, represent the main source of energy for cooking and heating activities, and so, health effects due to air pollution stemming from these activities in such areas is a major concern (Zhang & Smith, 2007). Similarly, in India, conservative estimates indicate that up to 550 000 premature deaths can be ascribed to the use of biomass fuels annually in population groups reliant on solid fuels for heating and cooking purposes (Smith, 2000).

Domestic burning of solid fuels such as coal and wood for cooking and heating purposes, contributes significantly to the high levels of ambient and indoor PM levels in many South African communities, particularly in the winter months (Engelbrecht *et al.,* 2000; Terblanche *et al.,* 1992b). In the South African context specifically, no-income and low-income communities make up 45% of the population, indicating that exposure to high air pollution levels is a great concern, as people living in these communities make use of domestic burning practices (Stats SA, 2015). Here, no-income households are defined as households that survive off no income at all throughout the year, and low-income is defined as a household that has an annual income of between R1.00 and R 19 200.00 (Stats SA, 2015).

Historically, in South Africa, working-class communities were built in close proximity to industrial hubs, mines and power stations (Dlamini, 2007; Norman *et al.,* 2007; Kimemia & Annegarn, 2011). These areas have become characterised by high population densities. Increased levels of air pollution and associated health risks are also observed here (Friedl *et al.,* 2008). Research has shown that, even though such areas have access to electricity, electrified households will typically continue to use dirty fuels for cooking- and

space-heating activities, as these fuels are less expensive than electricity (WHO, 2006; Nkosi *et al.,* 2017). This is particularly the case in many communities on the South African Highveld, Mpumalanga, which is home to most of South Africa's coal mines, and where coal is readily available and cheap (Balmer, 2007; Friedl *et al.,* 2008).

"The survey of energy related behaviour and perception in South Africa" (South Africa, 2012a) indicates that households, especially those in no-income and low-income communities, tend to rely on a multitude of energy sources, irrespective of their electrification status. This contradicts prevailing energy transition theories and the 'energy ladder' model, which have typically assumed a straightforward, uni-directional shift from traditional to modern energies and appliances once households are provided with electricity (South Africa, 2012a). Dirty fuels have been found to be used primarily for cooking and space heating activities, whereas electricity has been found to be used mainly for lighting, entertainment and refrigeration purposes (Engelbrecht *et al.,* 2002).

Four (4) factors have proven especially significant in determining the energy consumption patterns of households in South Africa: namely, rural-urban location, climatic conditions and the associated space heating requirements in winter months, as well as proximity to the country's coalfields (South Africa, 2012a). In Mpumalanga, 26% of households use coal, this represents the highest of any of the nine provinces and stands at nearly four (4) times the national average (7%). This reflects the proximity of these communities to some of the country's major coalfields (South Africa, 2012a).

Among the many pollutants emitted during domestic combustion processes, PM species have emerged as the most critical pollutants in almost all urban areas of the world (Health Effects Institute, 2017). These pollutants have been shown to have a significant impact on human health and the ecology of impacted environments (Yadav *et al.,* 2014). Industries, waste burning, dirt roads and traffic, all represent sources of PM in low-income communities (Friedl *et al.,* 2008). Of all sources of air pollution that cause negative health effects in South Africa however, domestic sources have by far the largest impact (Engelbrecht *et al.,* 2000; Mdluli, 2007; Friedl *et al.,* 2008; Kimemia *et al.,* 2016). This statement is supported by studies which estimate that ambient air pollution was responsible for 4637 deaths in the year 2000 and that indoor air pollution caused 2489 deaths for the same year in six (6) metropolitan areas within South Africa (Norman *et al.,* 2007).

2.4 Particulate matter concentrations and variability in low-income communities

2.4.1 Ambient and indoor particulate matter

Concentrations of airborne pollutants, such as PM originating from domestic burning, are governed by a combination of complex large- and local-scale atmospheric phenomena. Overall, the temporal and spatial variability of airborne PM is influenced by prevailing meteorology including synoptic scale circulation, atmospheric stability and local-scale air flow patterns (Gatebe *et al.,* 1999; Mkoma & Mjemah, 2011; Dagsson-Waldhauserova *et al.,* 2016). Times of air stagnation, characterised by high pressure, low winds, clear skies and inversions, for example, are responsible for the highest pollution concentrations (Zubkova, 2003; Alvarado & Prinn, 2009). Conversely, good atmospheric mixing and dilution conditions lead to lower concentrations (Terblanche *et al.,* 1992a; Briggs *et al.,* 1997; Riekert, 2011). Ultimately, PM concentrations in the atmosphere are a complex function of various sources of pollution and the capacity of the natural- and anthropogenic environment to disperse, dissipate and adsorb pollutants stemming from these sources (Cohen *et al.,* 2004).

Various literature sources have acknowledged that ambient pollution levels alone are not necessarily indicative of the concentrations of air pollution that humans in low-income communities are exposed to on a daily basis (Bruce *et al.,* 2002; Ferro *et al.,* 2004; Diapouli, 2011; Lim *et al.,* 2012). Exposure in such communities is a function of time spent in proximity to various pollution sources present in numerous micro-environments (Vette *et al.,* 2001). Even though emissions are more often than not dominated by outdoor sources, people spend the majority of their time in the indoor environment, where indoor sources exist. Significantly, it has been found that exposure, as a function of the degree of pollution in places where people spend their time, to a gram of pollution released indoors is likely to cause many times more harm than exposure to a gram released outdoors (Smith & Mehta, 2003; Norman *et al.,* 2007). Activities which create and influence indoor sources of indoor particulate matter are discussed below.

Significantly, though currently still in an unpublished draft format, the National Department of Health has developed a "Guideline for Monitoring Domestic Indoor Air Quality" (South Africa, 2017). Its intention is to present indoor air pollution limit values, which are to act as a "trigger to initiate action" to reduce

indoor air pollution, rather than to present a limit for regulatory purposes, as it is virtually impossible to limit what people breathe in their own homes. Indoor PM_{10} limit values correspond with current ambient air quality standard values for PM_{10} (South Africa, 2017). These guidelines emphasise the importance of taking into account indoor concentrations and sources when designing necessary mitigation strategies to reduce air pollution in low income communities.

2.4.2 Variability of particulate matter levels in a low-income context

It has commonly been assumed that intra- and even inter-urban PM concentrations are largely homogenous in nature and that the use of a single monitoring site to measure ambient concentrations to draw compliance-related conclusions with relevant air quality standards is sufficient to make health-based decisions (Burton *et al.*, 1996; Wilson, 2006; Morakinyo *et al.*, 2017). Whilst this assumption may hold true in first world country cities more so than not (although, many would argue that this assumption could also be refuted), this is an assumption that cannot easily be made in a low-income community context in the developing world, where domestic burning practices are prevalent and poor air quality is a daily reality and where a high variability of air pollution concentrations has been demonstrated (Bruce *et al.*, 2000; Ezzati & Kammen, 2002; Health Effects Institute, 2017).

The high variability of particulate concentrations within low-income communities is complex and is influenced by a variety of factors (Shilton *et al.*, 2002). Primarily, the variation of ambient PM concentrations in an urban environment is controlled by emissions, transport, transformation and loss processes in the atmosphere and how these processes change throughout the day and across the year (Yadav *et al.*, 2014). This means for instance, that concentrations of suspended PM tend to vary with shifting seasons (Ali *et al.*, 2015). In a low-income community context, because low-level burning activities most often correspond with cooking and heating needs, it makes sense that such activities would increase during winter months when the need to keep indoor environments warm, increases. Consequently, it has been shown that the PM concentrations in the ambient and indoor environments in the winter months are much higher than those measured in the summer months (Song *et al.*, 2015).

The concentrations to which individuals are exposed in a low-income setting are also dependent on diurnal temperature- and social behaviour patterns. Typically, a bi-modal distribution is most representative of diurnal trends of PM concentrations: Two concentration peaks occur during the day, the first occurs during the early hours of the morning and the second during the later afternoon /early evening, which each coincide with the main burning periods (Yadav *et al.,* 2014).

In the above paragraphs, it has been alluded to that air pollution in an indoor environment is often just as bad or worse than in the ambient environment. This represents an example of how intra-urban spatial factors can result in PM concentration variability. In many cases in low-income areas, a cause of high indoor PM concentrations is the penetration of external emissions of ambient origin into the indoor environment (Wilson *et al.,* 2000; Guo *et al.,* 2010; Hoek *et al.,* 2008; Orru *et al.,* 2014; Yangyang *et al.,* 2015). Conversely, by cumulatively considering the emissions caused by domestic burning activities indoors, outdoor PM concentrations increase when household smoke is emitted into the atmosphere (Morawska *et al.,* 2001).

Studies on indoor PM concentrations associated with various household fuels from homes in a wide range of countries have identified that short-term, peak concentrations of PM_{10} for instance, can lie within the range of 300 to 3000 (or more) micrograms per cubic meter ($\mu g/m^3$) (Bruce *et al.,* 2002). To put this into context, the South African annual National Ambient Air Quality Standard for PM_{10} is 40 $\mu g/m^3$. The equivalent daily PM_{10} standard is 75 $\mu g/m^3$ which is one to two orders of magnitude lower than levels seen in many homes in developing countries (Bruce *et al.,* 2002).

Socio-economic factors play a large role in the determination of the variability of indoor PM concentrations. These include (i) insulation and structural integrity of a household; (ii) the type of house (size and design); (iii) the cooking and heating devices as well as the dominant solid fuel type used, and finally, (iv) the burning habits or practices of a household (Nkosi *et al.,* 2017). Ultimately, all these features determine the amount of solid fuel burnt, which, in turn, determines the emissions to the atmosphere or the indoor environment (Scorgie *et al.,* 2003).

Insulation and structural integrity of a house as well as the house design influence the ventilation and volume of air that needs to be warmed and kept warm during the winter months. The cooking and heating

device, as well as its maintenance determines which fuel and how much of it is utilized (Makonese *et al.*, 2017). Additionally, the fuel characteristics (calorific value, moisture content and density) and burning practices (lighting method, secondary airflow control, type of food cooked, or use of multiple stoves or fuels) have a significant influence on the emission rate (Ezzati & Kammen 2002). In a most recent study, it was demonstrated that using different ventilation rates and ignition methods alone can cause $PM_{2.5}$ emission factors to range between 0.2 and 3.3 g/MJ when using D-grade coal in a domestic coal burning brazier (Makonese *et al.*, 2017).

2.5 Relationships between ambient, indoor and personal particulate matter concentrations

Understanding the relationships between indoor and ambient (outdoor) PM concentrations in different spatial and temporal contexts is important for air quality management in the domestic setting. In order to improve exposure understanding and to develop efficient regulatory guidelines for PM, sense needs to be made of how these relationships are influenced by different environmental conditions and also by societal habits (Morawska *et al.*, 2001; Vette *et al.*, 2001). It has been found that, when comparing ambient, indoor and personal PM concentrations with each other, ambient concentrations are typically lower than indoor concentrations, and indoor concentrations are typically lower than personal PM concentrations (Adgate *et al.*, 2002). Simultaneous measurements of these three parameters have only shown weak to moderate correlations between them, highlighting their complex relationship, and at the very minimum, indicating that the sources in the ambient and the indoor environment are different (Mohammadyan *et al.*, 2017). It follows then, that the more dissimilar the indoor and ambient PM loadings, the more likely it is that the sources are different. A good relationship between ambient and personal or indoor and personal PM concentrations means that a person wearing a personal monitoring device spent a considerable proportion of time within the environment in question (Janssen *et al.*, 2005).

Measuring ambient, indoor and personal PM concentrations at the same time to investigate their relationships creates the best opportunity to understand what people in communities breathe and whether ambient or indoor concentrations alone can simply be used as a personal exposure surrogate (Nakai & Tamura, 2008). If ambient, indoor and personal PM concentrations measured across various seasons are similar in trend, magnitude and variation, it can be carefully assumed that ambient measurements can

represent a surrogate for personal concentrations; if this is not the case however, then it can be argued that ambient measurements do not at all represent what people breathe and that straightforward compliance-related decisions cannot be made using ambient measurements only (Huang *et al.,* 2015).

2.6 Relevance of this study

The scientific community has for some time raised the concern that air quality in low-income communities in sub-Saharan Africa surpasses "safe-to-breathe" concentrations, guided by ambient standards (Chen & Smith 1991; Bruce *et al.,* 2000; Scorgie *et al.,* 2003; Josipovic *et al.,* 2010; Garland *et al.,* 2017; Health Effects Instutute, 2017). Most studies have treated ambient, indoor and personal air pollution separately. Limited studies in South Africa have simultaneously considered air quality in both the ambient and the indoor environment for extended periods of time and concurrently considered personal exposure to air quality (Terblanche *et al.,* 1992a; Terblanche *et al.,* 1992b; Engelbrecht *et al.,* 2000; Engelbrecht *et al.,* 2002; Mdluli, 2007). Previous findings have pointed to the fact that ambient air pollution levels, at times, exceed ambient standards, that indoor concentrations are higher than ambient concentrations (Petzer, 2009) and that personal exposure to PM is unacceptably high (Terblanche *et al.,* 1992b). No South African studies have been conducted that have simultaneously measured and assessed the relationships between ambient, indoor and personal PM concentrations at such a large scale and this across various seasons. Similarly, this is the first study to include personal GPS monitor readings to help better define personal exposure in different micro-environments.

This research seeks to confirm findings that have been made in previous studies which have postulated that ambient, indoor and personal PM concentrations measured in low-income communities in South Africa at times exceed air quality standards. Furthermore, this study brings the international debate of whether stationary ambient air quality monitoring stations are adequate proxies to use for compliance-related decisions as well as for epidemiological enquiries into the South African arena. For the first time in South Africa, a study corresponds simultaneously logged personal GPS readings and personal PM concentration measurements to better understand time-activity patterns of an individual in a low-income community context in various micro-environments and the PM concentrations breathed in those environments. An unprecedently rich set of ambient, indoor and personal measurements, which were

collected during two separate pilot studies conducted for Sasol and Eskom, respectively in KwaDela and KwaZamokuhle, form the basis of this research.

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This chapter presented the literature consulted to place this study into context. Main points to carry through the remainder of the thesis are that PM concentrations in communities that rely heavily on solid fuels for heating and cooking purposes have been shown to, at times, exceed ambient standards. The ambient, indoor and personal PM concentrations measured in these environments are highly variable in space and time. High variability of PM concentrations in space and time make it difficult to use ambient measurements taken at one stationary ambient monitoring station as proxy data to represent air quality in the entire community. Assessing personal exposure and intake doses is a complex task and requires information on exposure concentrations and personal inhalation rates. The following chapter discusses the study design, how data for the study were collected and then how these data were analysed.

Chapter 3 Research Methodology

In this chapter, the methods used to collect and analyse the data used for this study are outlined in detail. As the data were collected at two different sites and as part of two different study campaigns, emphasis is placed on the detailed provision of information to ensure it is understood how, when, where and why the data were collected. The study for this dissertation forms an amalgamation of two similar study designs created for Sasol and Eskom's air quality offset pilot studies by NWU and The NOVA Institute. Limitations and assumptions taken into account in the study design and result interpretation are elaborated upon.

3.1 Study area

3.1.1 Geographical location of the study sites

Two low-income communities, located within the Highveld Priority Area (declared in 2007), Mpumalanga, South Africa, have been chosen for the purposes of this comparative study, KwaDela and KwaZamokuhle (Figure 3.1 and Figure 3.2). An airshed is declared as a designated Air Quality Priority Area because ambient air quality standards are being exceeded, or may be, in the future (South Africa, 2007). Air quality on the Highveld is characterised by elevated concentrations of criteria pollutants stemming from industrial and non-industrial sources (South Africa, 2016; Garland *et al.,* 2017). Notable non-industrial sources of criteria pollutants affecting air quality in many low-income communities on the Highveld are domestic burning activities (Mdluli, 2007; Kimemia & Annegarn, 2011). Basic demographic statistics illustrate that people living in both KwaDela and KwaZamokuhle are highly dependent on coal as a readily available energy source for domestic cooking and heating, and it has been shown that these practices have a negative impact on the air quality in KwaDela (Table 3.1) (Nkosi *et al.,* 2017).

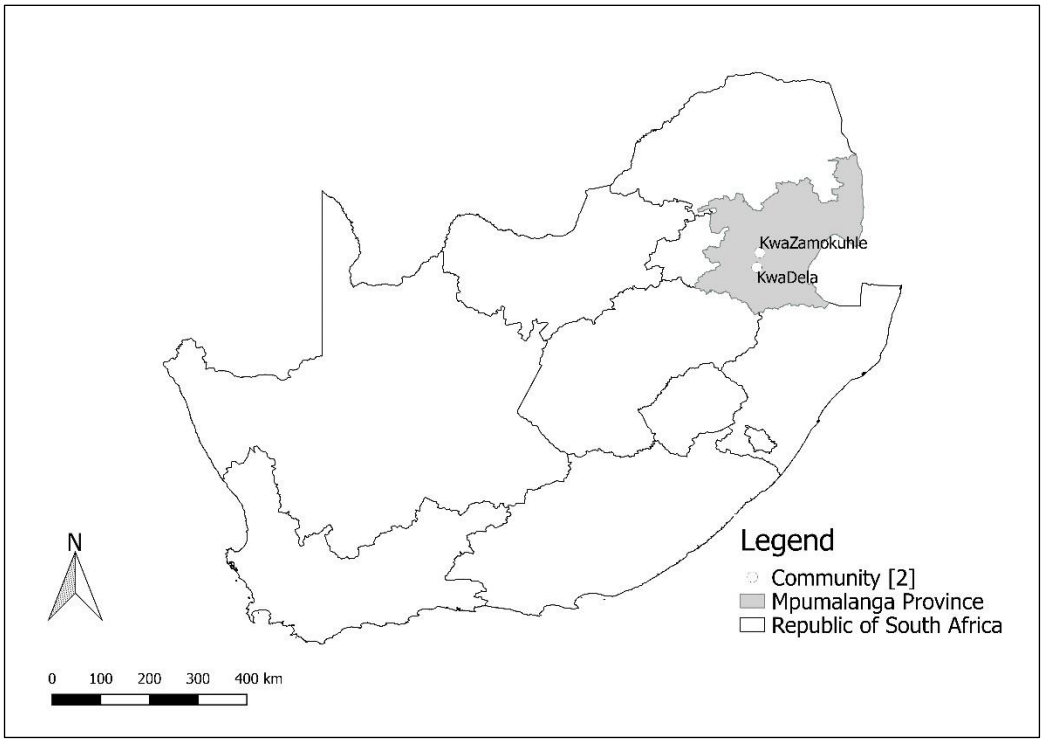

Figure 3.1. Map of study sites in relation to each other in the Mpumalanga Province, South Africa

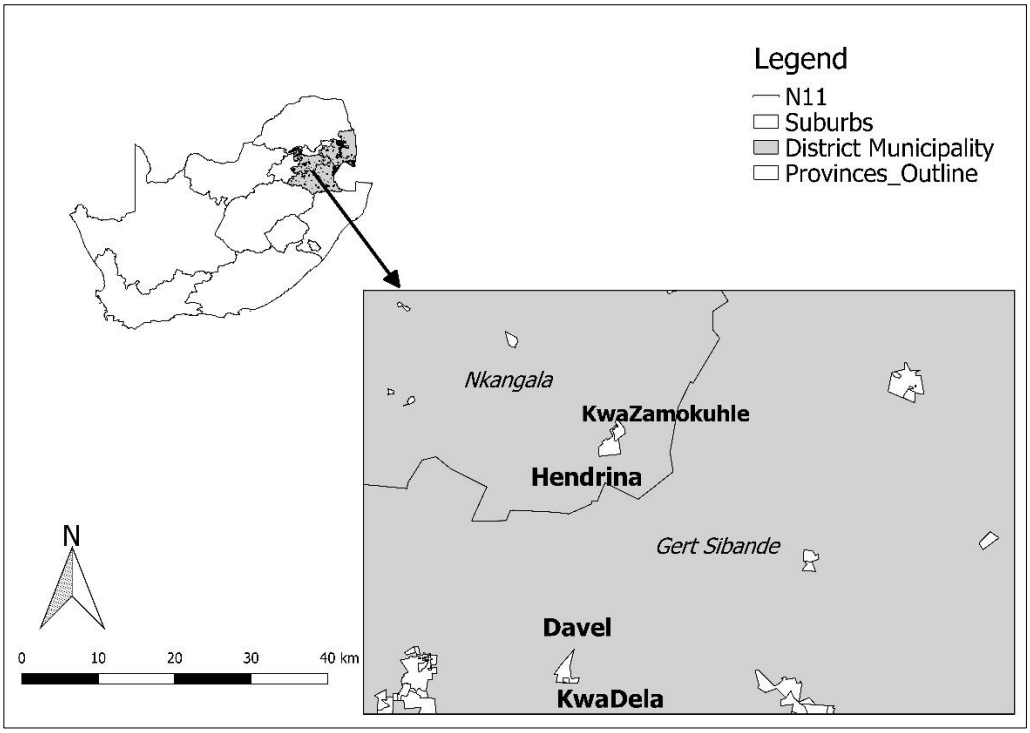

Figure 3.2. Overview of study sites in relation to relevant suburbs and district municipalities

KwaDela is a small community (population of 3 781) which lies in the Msulkaligwa Local Municipality and the Gert Sibande District. It is located next to the N17 between Bethal and Ermelo. Davel is the closest other town, situated just north of KwaDela (Figure 3.3). Apart from railroad traffic, road traffic on the N17 and local traffic within Davel and the community itself, solid fuel burning from industry and domestic households as well as waste burning can be considered the main contributors to ambient air pollution in KwaDela (Msukaligwa Local Municipality, 2010).

KwaZamokuhle (population of 20 427) is situated about 40km north-east of KwaDela and lies within the Nkangala District Municipality just north of the town of Hendrina and close to Hendrina Power Station. Diurnal timeseries analyses comparing hourly average PM concentrations in KwaZamokuhle and nearby Hendrina have confirmed that KwaZamokhle's air quality is characterised by early morning and late afternoon-/ evening peaks, indicating domestic burning activities associated with heating and cooking in the early mornings and late afternoons (Eskom, 2017).

Coal resources on the Mpumalanga Highveld are an easy-to-access energy source for households in this region, making it the primary source of fuel for cooking and heating in many low-income communities. Numerous coal mines and twelve coal fired power stations are situated within the Highveld region, bearing testimony to the fact that coal is plentiful.

Table 3.1. Relevant community statistics for KwaDela and KwaZamokuhle taken from the Census 2011 - an overview (Stats SA, 2012b)

	KwaDela	**KwaZamokuhle**
Coordinates	26.4633 S, 29.6644 E	26.1346 S, 29.7317 E
Municipality	Msukaligwa local	Steve Tshwete local
Total population	3 781	20 427
Number of households	982	5 874
People per household	3.9	3.5
People living with < R4 800.00/ month	21.6%	16.9%
Use of coal as a source for heating and cooking *	46.7% and 42.2%, respectively	34% and 31.2%, respectively
Use of electricity for lighting purposes	96.7%	89.2%

*primary energy carrier for these purposes

3.1.2 Meteorology in KwaDela and KwaZamokuhle

Warm and temperate climatic conditions prevail in KwaDela and KwaZamokuhle throughout most of the year. The communities lie within a summer rainfall region and precipitation ranges from 83 - 132 mm/month in summer to 5 - 29 mm/month in winter. Highest average maximum temperatures are experienced from December to March (~24 - 25°C) and lowest average minimum temperatures from May to August (~ 0 - 4°C) (Climate-Data, 2017). Winds are highly variable with more prevalent easterly and westerly components.

During the study campaign the stark contrast between average morning/ night minimum and average daytime maximum temperatures during the winter months were noted (Table 3.2 and Table 3.3). Temperature, relative humidity and pressure patterns showed a diurnal cycle.

Table 3.2. Descriptive statistics of 1-hour resolution meteorological data for each of the campaigns in KwaDela

		Wind Speed (m/s)	**Temperature (°C)**	**Relative Humidity (%)**	**Solar Radiation (W/m^2)**
Winter 2013	Min	0.0	-4.5	5.3	0.0
	Max	12.9	28.2	100.0	804.1
	Ave	3.9	10.8	52.1	174.8
Summer 2014	Min	0.0	3.1	8.6	0.0
	Max	12.1	30.1	100	1439.8
	Ave	3.1	16.4	71.2	208.4
Winter 2014	Min	0.0	-3.8	3.2	0.0
	Max	15.7	34.1	100	1014.1
	Ave	3.4	11.9	44.2	203.6
Summer 2015	Min	0.0	6.7	14.8	0.0
	Max	13.2	32.6	99.2	1099.9
	Ave	2.9	17.7	68.8	213.5

Table 3.3. Descriptive statistics of 1-hour resolution meteorological data for each of the campaigns in KwaZamohule

		Wind Speed (m/s)	Temperature (°C)	Relative Humidity (%)	Solar Radiation (W/m^2)
Spring 2015	Min	0.0	11.3	5.4	0.0
	Max	11.9	34.6	100	7999
	Ave	3.2	24.0	13.9	203.6
Summer 2016	Min	0.0	10.9	8.4	0.0
	Max	9.7	32.8	100	7999.0
	Ave	2.2	23.0	68.7	177.5
Winter 2016	Min	0	-6.4	0.93	0
	Max	10.3	31.1	100	7999
	Ave	2.3	11.5	47.8	177.9

3.2 Data collection

3.2.1 Data collection as part of larger scale studies

Ambient, indoor and personal PM concentrations were measured as part of campaigns in KwaDela and KwaZamokuhle, respectively. Questionnaire based surveys were also conducted to better understand the energy use patterns of the respective areas and to contextualise the data stemming from ambient air quality assessments. The campaigns in KwaDela and KwaZamokuhle were conducted from 2013 and 2014 onwards for Sasol and Eskom's air quality offset pilot studies and aimed to ultimately test the effectiveness of various air quality household offset interventions in a low-income community context to reduce ambient PM levels.

3.2.2 Air quality monitoring in the ambient and the indoor environment

A mobile ambient air quality monitoring station was set up to obtain continuous ambient concentrations of PM in both considered communities. PM_{10} and $PM_{2.5}$ were measured in the ambient monitoring stations using Horiba BAM 1020 and MetOne E-Bam monitors in KwaDela and THERMO Beta Gauges in KwaZamokuhle. These devices are instruments typically used for compliance monitoring purposes (Table 3.4 and Table 3.**5**) (Raja *et al.,* 2017). Basic meteorological data (temperature, humidity, pressure, wind

speed and direction, rainfall) were also monitored. Additionally, both campaigns made use of numerous individual stationary samplers, which were spread throughout the communities, to measure ambient PM_{10} and $PM_{2.5}$ concentrations in different locations across the settlements, to gain a better understanding of the spatial variability of PM concentrations (Figure 3.3 and Figure 3.4).

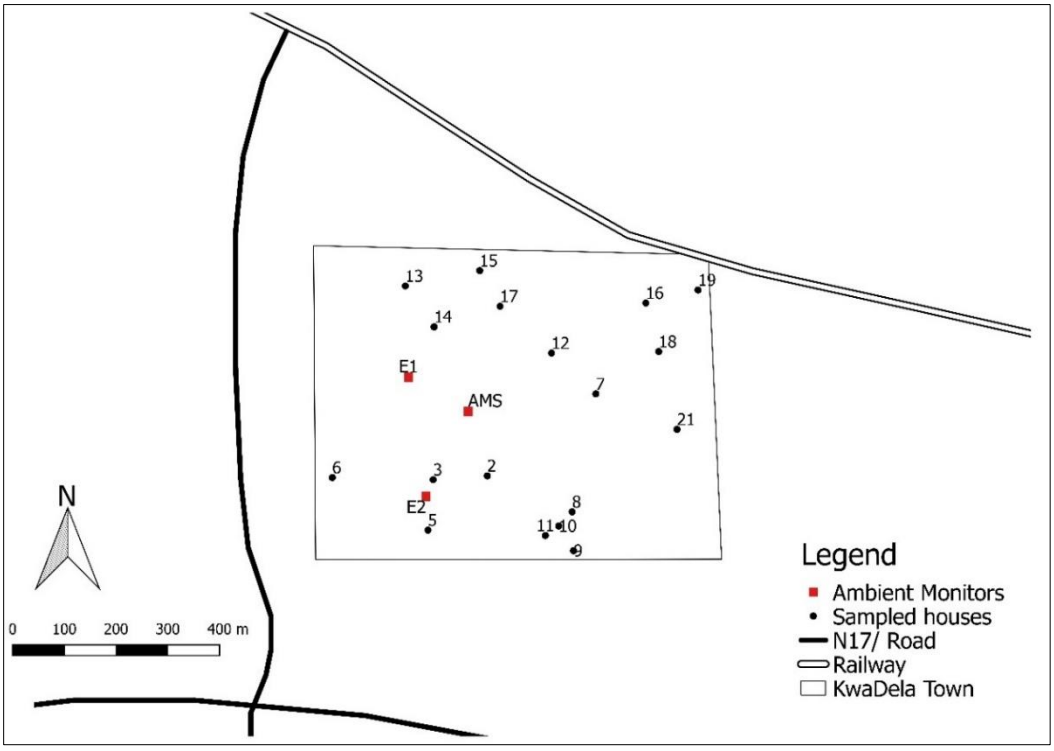

Figure 3.3. Overview of ambient and indoor monitoring sites located in KwaDela

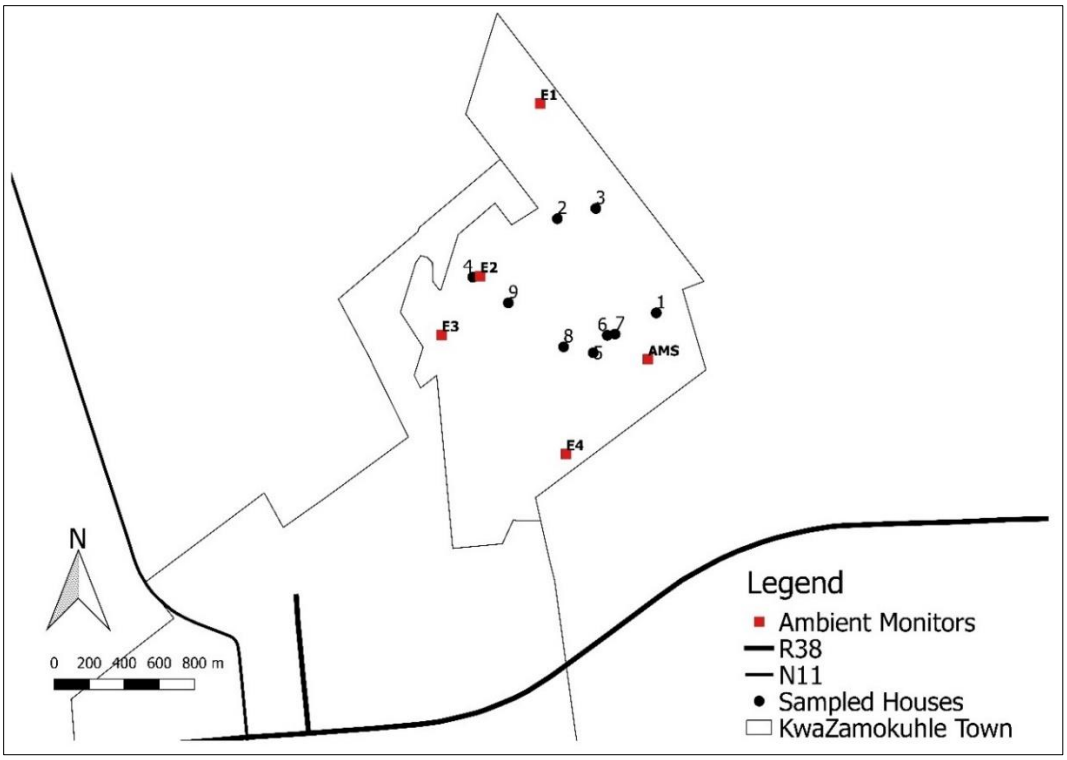

Figure 3.4. Overview of ambient and indoor monitoring sites located in KwaZamokuhle

Table 3.4. E-Sampler and E-Bam codes for in-text interpretation and orientation according to cardinal directions

E-Sampler /E-Bam number on map	**Code per E-Sampler according to cardinal directions for interpretation and orientation in text**	
	KwaDela	**KwaZamokuhle**
E1	KD-E1-NW	KZ-E1-N
E2	KD-E2-SW	KZ-E2-NW
E3	-	KZ-E3-W
E4	-	KZ-E4-SE

The sampling campaigns in KwaDela included winter (2013 and 2014) and summer (2014 and 2015) months, whilst the campaigns in KwaZamohule were undertaken in spring (2014), summer (2016) and winter (2016) months, to take into account seasonal variability of PM concentrations (Table 3.**5**).

Indoor air quality monitoring took place in 20 and nine (9) individual, semi-randomly selected and consenting households in KwaDela and Kwazamokuhle, respectively (Table 3.**6**). A multi-stage sampling method selected participating houses, where street blocks and one household from each street block were randomly selected. This method ensured a relatively even geographic distribution of monitored households in the two communities. The indoor monitoring equipment was typically placed in the kitchen or the living room of the household. Indoor PM_4 concentrations were measured using TSI DustTrak (Models 8520 and 8530) photometric monitors at 5-minute time intervals.

Personal exposure of a small number of community members in households in which indoor air pollution was monitored was measured as PM_4 at 5-minute time intervals using a TSI SidePak AM510 photometric monitor, which was deployed at a height equivalent to a person's breathing zone. Informed consent was given by those who wore personal monitors. To complement the PM measurements of the SidePak monitor, a few select individuals (middle-aged women) in KwaDela also carried along with them Global Positioning System (GPS) monitors which tracked their movement for a given period of time. It was a requirement of the study that only persons who spent most of their time in KwaDela were allowed to participate in this part of the study, so as to ensure readings were focused to concentrations experienced in KwaDela only.

The indoor and personal PM_4 measurements used have been corrected according to the specific photometric calibration factors obtained for both the DustTrak and SidePak instruments (Language *et al.*, 2015). As part of quality control and quality assurance procedures, the instruments within the mobile monitoring station were checked once a week during the sampling campaigns. The indoor instruments were zero calibrated and flow checked as per manufacturer's directions. The personal monitoring instruments were flow checked once a week and zero calibrated each day before sampling proceeded.

Table 3.5. Overview of ambient data collection in KwaDela and KwaZamokhule

	KwaDela	**KwaZamokuhle**
Source of data	Sasol Offset Pilot Study	Eskom Offset Pilot Study
	Social data	
Number of Households at which surveys were conducted	Total = 195	Total = 919 Good quality = 692
Date of surveys	August 2013 – July 2014	November 2014 – October 2015
Content of surveys	General household survey (energy use patterns) including a community health survey	General household survey (energy use patterns) including a community health survey
	Ambient PM measurements	
Measured pollutants	PM_{10}/ $PM_{2.5}$	PM_{10}/ $PM_{2.5}$
Other available data	Meteorological data	Meteorological data
Instrument type used	Horiba BAM 1020 (PM_{10}) – (beta ray attenuation), MetOne E-Bam ($PM_{2.5}$) (beta ray attenuation), 2 x MetOne E-Sampler (E1 = $PM_{2.5}$, E2 = PM_{10}) (Light-scattering aerosol monitors)	THERMO – Beta gauge (PM_{10} and $PM_{2.5}$) (non-step-wise beta ray attenuation) 4 x E-Bam Beta gauges (E1 – E4 = $PM_{2.5}$) (beta ray attenuation)
Flow-rate and set-up	Flow Rate 16.7 L.min-1 (actual or standard flow), automated span checks.	Flow Rate 16.7 L.min-1, automated span checks
Data resolution for this study	5 minutes intervals averaged into 60-minute interval data	5 minutes intervals averaged into 60-minute interval data
Location of main ambient monitoring station	Secondary School close to the centre of KwaDela	On church grounds in the east of KwaZamokuhle
Timeframes of campaigns	Winter 2013 (4 July – 27 September) Summer 2014 (10 February – 6 May) Winter 2014 (11 July – 17 September) Summer 2015 (11 February – 13 April)	Spring 2015 (2 September – 27 November) Summer 2016 (24 February – 19 April) Winter 2016 (12 July – 9 September)

Table 3.6. Overview of indoor and personal data collection in KwaDela and KwaZamokhule

Indoor PM measurements		
	KwaDela	**KwaZamokuhle**
Measured pollutants	PM_4	PM_4
Instrument type	TSI DustTrak Model 8530 (light-scattering laser photometers)	TSI DustTrak Model 8530 (light-scattering laser photometers)
Data resolution	5 minutes intervals averaged into 60-minute interval data	5 minutes intervals averaged into 60-minute interval data
Set-up	A 10-mm Nylon Dorr Oliver Cyclone inlet was used with each instrument, at a flow rate of 1.7 L.min-1, to acquire the required 50% cut size at 4 μm. The output for the particulate mass concentration is given in milligram per cubic meter (mg.m-3). An averaging period of five minutes was used. These instruments are factory calibrated using Arizona test dust.	A 10-mm Nylon Dorr Oliver Cyclone inlet was used with each instrument, at a flow rate of 1.7 L.min-1, to acquire the required 50% cut size at 4 μm. The output for the particulate mass concentration is given in milligram per cubic meter (mg.m-3). An averaging period of five minutes was used. These instruments are factory calibrated using Arizona test dust.
Number of households in which indoor monitoring took place	20	9
Timeframe	Winter 2013 (4 July – 27 September) Summer 2014 (10 February – 6 May) Winter 2014 (11 July – 17 September) Summer 2015 (11 February – 13 April)	Spring 2015 (29 September – 18 November) Summer 2016 (22 February – 20 April) Winter 2016 (12 July – 23 August)

Personal PM measurements		
Measured pollutants	PM_4	PM_4
Instrument type	TSI SidePak AM510 (light-scattering laser photometers)	TSI SidePak AM510 (light-scattering laser photometers)
Data resolution	5 minutes intervals averaged into 60-minute interval data	5 minutes intervals averaged into 60-minute interval data
Set-up	Scattering nephelpometers (laser has $\lambda = 680$ nm). The instruments are light weight and equipped with 10-mm Nylon Dorr-Oliver Cyclones effecting a 50 % cut-off at 4 μm. The battery life of the	Scattering nephelpometers (laser has $\lambda = 680$ nm). The instruments are light weight and equipped with 10-mm Nylon Dorr-Oliver Cyclones effecting a 50 % cut-off at 4 μm. The battery life of the

	personal monitors was between 8 and 12 hours. Individuals were therefore requested to carry the monitors only during the daytime 07H00 to 19H00.	personal monitors was between 8 and 12 hours. Individuals were therefore requested to carry the monitors only during the daytime 07H00 to 19H00.
Number of people wearing SidePaks	20 individuals	8 individuals
Time period of GPS measurement availability for one-individual-case-study	21-28 August 2013 (Individual was a middle-aged woman)	NA
Timeframe	Winter 2013 (4 July – 27 September) Summer 2014 (10 February – 6 May) Winter 2014 (11 July – 17 September) Summer 2015 (11 February – 13 April)	Spring 2015 (29 September – 18 November) Summer 2016 (22 February – 20 April) Winter 2016 (12 July – 23 August)

3.2.3 Measuring personal exposure to particulate matter concentrations in various micro-environments

One unique component of the study in KwaDela was to track the daytime movement patterns of consenting individuals within the community using personal monitors and mobile GPS monitoring devices (Table 3.6). The purpose of this exercise was to establish where individuals were exposed to the greatest PM concentrations. Micro-environments were identified by plotting all of the recorded GPS readings taken in KwaDela on a SPOT 6/7 (2015) satellite image of KwaDela using QGIS version 2.14.1 (Figure 3.5). This is how it was ascertained where individuals spent most of their time whilst wearing personal monitoring devices (notably, this was during day-time hours).

Figure 3.5. Examples of GPS coordinates plotted on a SPOT 6/7 image of KwaDela to help identify common micro-environments (The colours of the dots denote the movements of the various individuals wearing GPS monitors on different days. For the purpose of this study, the colours have no significance. This figure aims to illustrate movement patterns of individuals wearing the GPS monitors to assist in micro-environment identification and nothing more)

3.3 Data analysis

3.3.1 Characterising particulate matter concentrations at a community level

Differently averaged continuous ambient PM measurements were used for the purposes of statistical analysis. Microsoft Excel 2016 was used to conduct statistical analyses for summary purposes. Five (5)-minute average data were used to create hourly- and daily averaged data sets for PM_{10}, PM_4 and $PM_{2.5}$. Statistica 13.2 was used to create summary box plots to compare different daily average PM concentrations at a community level. For the purposes of averaging, the 99^{th} percentile was used to ensure results could be used to make compliance related conclusions. Where the daily average PM concentrations were derived, the geometric mean with its standard deviation, were considered. Data gaps were dealt with by means of mean-substitution and regression analyses considered pairwise deletion.

Statistica 13.2 was also used to create boxplots to compare averaged maximum values measured across the sampling points. Outliers and extreme observations were included in graphs and in analyses where median values are displayed but excluded where mean values are displayed as the mean is sensitive to outliers. Here outliers are defined as data points with a value greater/ smaller than the upper/ lower value of the box on the plot (i.e. the 25th and 75th percentile value) ± the coefficient of 1.5 multiplied by the difference between the upper and the lower value of the box. Extreme values plotted represent the same value, derived in the same manner, using two times the outlier coefficient (these are default settings in Statistica 13.2). Extreme values have been kept in these graphs to indicate events of extreme/ acute exposure.

As PM concentrations are influenced by seasonal variation, spring, summer and winter concentrations were considered separately in every analysis conducted. Where possible, comparisons were made between KwaDela and KwaZamokuhle.

3.3.2 Characterising particulate matter concentrations at a household level

Two households per community were selected in order to gain a better understanding of household-level PM characteristics and relationships. The households were selected based on the fact that indoor and personal PM measurements were conducted for these selected houses and so *cases* could be formed, allowing for seasonal comparison of ambient, indoor and personal PM concentrations. A *case* represents a dataset which contains different parameters which were available simultaneously, i.e. data were available for ambient PM_{10} and $PM_{2.5}$ as well as for indoor and personal PM_4 measured during the same time periods, allowing direct comparisons between these PM types. The number of *cases* typically represents the number of indoor sampling campaigns that took place in a community. Across the seasonal campaigns, a total of 33 *cases* were identified in KwaDela and a total of 24 *cases* were identified in KwaZamokuhle (Table 3.7 and Table 3.8). For this study, house 3 and 11 were chosen in KwaDela and house 3 and 9 were chosen in KwaZamokuhle (Table 3.9).

Table 3.7. Overview of cases used for comparative analyses in KwaDela

Campaign	*Case* name	Campaign	*Case* name
Winter 2013 (W13)	H2	**Summer 2014 (S14)**	H3*
	H3*		H5
	H4		H11*
	H10		H13
	H11*		H15
	H13		H18
	H14		

Campaign	*Case* name	Campaign	*Case* name	
Winter 2014 (W14)	H5	**Summer 2015 (S15)**	H1	H11*
	H6		H3*	H13
	H14		H4	H18
	H15		H5	H21
	H18		H6	H22
	H19		H8	H23
	H22		H10	

Note: Going forward, a specific *case* is referred to by combining the season in which a sampling campaign took place with the number of the house in which indoor and personal monitoring took place, e.g. *case* W13H2 represents the ambient, indoor and personal measurements taken at the same time in winter 2013 in house 2 and *case* S14H18 represents the ambient, indoor and personal measurements taken at the same time in summer 2014 in house 18.
*Cases chosen for the in-depth household-level analyses

Table 3.8. Overview of cases used for comparative analyses in KwaZamokuhle

Campaign	*Case* name	Campaign	*Case* name	Campaign	*Case* name
Spring 2015 (Spg15)	H3*	**Summer 2016 (S16)**	H1	**Winter 2016 (W16)**	H1
	H4		H2		H2
	H5		H3*		H3*
	H7		H4		H4
	H8		H5		H5
	H9*		H6		H6
			H7		H7
			H8		H8
			H9*		H9*

**Cases* chosen for the in-depth household-level analyses

Table 3.9. Overview of cases chosen for household-level analyses

KwaDela	**W13**		**S14**		**S15**	
	Dates	**Ambient Temp**	**Dates**	**Ambient Temp**	**Dates**	**Ambient Temp**
H3	24/7-21/8	10.12±5.49	10/2-26/2	18.56±4.59	11/2-2/3	19.86±5.22
H11	21/8-29/8	12.85±5.43	5/3-18/3	17.48±2.70	11/2-2/3	19.86±5.22
KwaZamokuhle	**Spg15**		**S16**		**W16**	
	Dates	**Ambient Temp**	**Dates**	**Ambient Temp**	**Dates**	**Ambient Temp**
H3	29/9-26/10	22.36±6.29	7/3-24/3	19.06±4.49	27/7-23/8	10.27±8.03
H9	27/10-18/11	19.26±7.04	23/2-7/3	20.32±5.28	27/7-23/8	10.27±8.03

Statistica 13.2 was used to plot daily average bar charts for every PM type measured per *case* for every season. Microsoft Excel 2016 was used to plot hourly average timeseries to ascertain the diurnal variations of PM concentrations at an ambient, indoor and personal level in direct comparison. Hourly indoor PM_4: personal PM_4 ratios and indoor PM_4: ambient $PM_{2.5}$ ratios were ascertained for the chosen houses and also plotted on an hourly average timeseries graph.

3.3.3 Comparing ambient, indoor and personal particulate matter concentrations and understanding their relationships

Simple box plots were plotted for maximum hourly concentrations for every *case* for every sampling campaign by using Statistica 13.2. Medians, 25^{th} and 75^{th} percentiles as well as minimum and maximum concentrations were plotted for each PM type for each *case*. Outliers and extreme observations were included in the graphs to show extreme/ acute exposure events.

Two different sets of regressions were plotted of hourly, lognormally transformed datasets using Statistica 13.2 and Microsoft Excel 2016 to ascertain whether there was a noteworthy relationship between ambient, indoor and personal PM concentrations. Data points above the 90^{th} percentile were excluded from this analysis, as regressions are sensitive to outliers. The coefficient of determination resulting from the regression (R^2) analysis was used to determine how the percent of variation in one PM type could be attributed to the variation in another PM type. The closer an R^2 value is to 1, the greater the likelihood that the variation in one PM type could be attributed to the variation in another PM type:

1. To ascertain whether or not there were notable relationships between PM type concentrations measured at a household-level, regressions were plotted for each and every *case*, for each and every ambient, indoor and personal PM combination (i.e. indoor and personal PM_4 vs ambient PM_{10}, indoor and personal PM_4 vs ambient $PM_{2.5}$, indoor and personal PM_4 vs ambient $PM_{2.5}$ measured at E-Sampler-1/ E-Bam 1, E-Sampler 2/ E-Bam 2 and so forth). Regressions were also plotted between indoor and personal- as well as between the various ambient PM types themselves (E.g. E-Sampler 1 vs E-Sampler-2 or E-Bam 1 vs E-Bam 2 etc.). Results of these regression analyses have been illustrated by using the *cases* chosen for the two-household case study (Chapter 5).

2. Regressions that indicated more overarching relationships between indoor and ambient PM concentrations at a community-level were plotted by considering total daily- and hourly average concentrations as well as daily- and hourly maxima and plotting these against each other for each community. To illustrate any overarching community-level trends the coefficient of determination resulting from every regression analysis was then plotted against its corresponding slope in a scatter plot using R (version i386 3.3.1).

Additional to the above, relationships between indoor and personal as well as ambient and indoor PM concentrations were explored through the derivation of ratios, where

$$\text{Personal } PM_4/\text{ Indoor } PM_4 \text{ ratio} = Ci/\ Cp \qquad (3)$$

and where Ci represents indoor PM concentrations and Cp represents personal PM concentrations. Ratios >1 indicate higher indoor PM concentrations and ratios <1 indicate higher personal concentrations. If the ratio = 1, it means that indoor and personal PM concentrations are the same, and thus it can be extrapolated that the individual wearing the personal monitor is in the vicinity of the same source of PM that determined the indoor concentrations measured. Similarly,

$$\text{Indoor } PM_4/\text{Ambient } PM_{2.5} \text{ ratio} = Ci/Ca \qquad (4)$$

where Ca represents ambient $PM_{2.5}$ concentrations. On the same note, a ratio < 1 indicates higher $PM_{2.5}$ concentrations and a ratio of >1 indicates higher indoor PM_4 concentrations. If the ratio = 1, it means that the same sources are influencing the magnitude of the indoor and ambient PM concentrations.

3.3.4 Assessing personal exposure to particulate matter in different micro-environments

Personal PM_4 concentration measurements from 21 – 28 August 2013 were, where possible, paired with the GPS tracking data at ten-minute intervals, to ascertain the PM_4 concentrations to which an individual was exposed in a given location and at a given time period (Table 7.1 in Annexure C). PM_4 concentrations were paired to a specific micro-environment as explained in section 3.2.3 above.

A map was created in QGIS to illustrate the above described for one day, 21 August 2013. For the sake of anonymity, polygons were drawn around the households within which the individual spent time. Dots representing the specific individual's locations were coloured in a graduated manner, and so the colour of the dot represents the PM_4 concentration measured by the SidePak monitor at a given time and in a given location. Indoor PM_4 measurements for the house in which the individual spent the most time were included in the analysis. Hourly average diurnal timeseries were plotted in Excel for personal measurements taken from the 21-28 August 2013.

Indirect, time-weighted, integrated exposure concentrations as well as time-weighted, integrated potential intake doses were ascertained by using the U.S. EPA equations (1) and (2) listed in Chapter 2 (Table 7.2 in Annexure D). Input data consisted of indoor PM_4 measurements and ambient $PM_{2.5}$ measurements as well as information gathered on the averaged time-activity patterns of the person who wore the GPS monitor. PM_4 and $PM_{2.5}$ were directly compared, based on rationale explained in section 3.5 below. Direct intake doses were derived using the personal measurements available for the case-study. Short-term inhalation rates (m^3/min) for an average middle-aged woman at light intensity activity, as recommended by the U.S. EPA, were used for the purposes of this exercise. This was then converted to an equivalent daily breathing rate (0.012 m^3/min *60 *24 =17.28 m^3/day) (U.S. EPA, 2011). It must be noted that the GPS/ Personal PM_4 data used do not represent a full day's worth of data, and hence the short-term breathing rate was deemed appropriate. High resolution ambient $PM_{2.5}$ and indoor PM_4 data were also used to ascertain indirect dose inhalation rates for the exact time periods during which personal

measurement were available, to see whether or not the resulting doses would differ substantially from the directly derived dose rates.

3.4 Ethical considerations

This research was conducted in an ethically responsible manner and relevant norms and standards were complied with. Due to the health-related focus of the study, the Faculty of Natural Science and Agriculture of the North West University referred the ethical clearance of the project to the National Health Research Ethics Council (HREC). Two separate project proposals, one for KwaDela and one for KwaZamokuhle, were reviewed and monitored by the national HREC. Ethical clearance numbers for KwaDela (NWU-00066-13-A3) and for KwaZamokuhle (NWU-0158-14-S3) were received. The identity of all individuals, whose movements, locations and personal information were tracked in this study remain anonymous and data was only gathered if explicit consent was given to do so.

3.5 Limitations and assumptions

Though main findings resulting from this study are clear, assumptions are being made that these findings represent a true reflection of PM concentrations to which individuals are exposed in the indoor and ambient environment in KwaDela and KwaZamokuhle, respectively. The large intra- and inter-urban variability of the concentrations measured, makes it difficult to quantify and summarise concentrations with certainty and it is impossible to draw statistically significant conclusions, unless adequately large sample sizes are considered. The size of a study design of this nature is limited however by financial- and human resources. It is a time-consuming exercise and tedious to ensure the equipment is maintained to manufacturer's standards and that it is up and running to ensure data collected can be adequately used for research purposes. Though large variability in ambient, indoor and personal PM concentrations in this study is evident, an assumption is being made that the snapshot in space and time that is presented here, gives a realistic indication of what is measured on the ground in these communities on a day-to -day basis.

The results ascertained are highly variable and highly context specific. This means for instance that the PM concentrations measured in one location at a given time will not necessarily represent the PM concentrations measured at a different location at the same time. Even though temporal, spatial and socio-economic factors are accounted for to make sense of the data presented, these conclusions are drawn with caution, and cognisant of the fact that other factors not mentioned in this study could well have played a role in determining PM concentrations measured at any given moment in time.

A further assumption that is being made is that PM concentrations of different size fractions measured in the ambient and the indoor environment can easily be compared. This means that PM_{10} and $PM_{2.5}$ concentrations in the ambient environment are being compared with PM_4 concentrations in the indoor environment to ascertain relationships. This is considered possible because the PM size fractions represent sub-sets of each other. PM_4 concentrations measured in the indoor environment and with personal monitors have been directly compared to $PM_{2.5}$ concentrations measured in the ambient environment. It is assumed that, as most indoor PM concentrations stem from domestic burning practices, indoor PM will more than likely fall under the $PM_{2.5}$ size fraction, and so the PM_4 concentrations measured will likely be represented to a large degree by particles < 4 microns. Additionally, as there are no ambient standards for PM_4, it is being assumed that if daily PM_4 concentrations exceed the daily average PM_{10} standard, non-compliances with the NAAQS are being incurred. This is in line what has been drafted in the National Guidelines for Monitoring Domestic Air Quality, which suggest indoor PM_{10} limit values equal to those of the ambient PM_{10} limit values of the NAAQS (South Africa, 2017).

Another constraint is represented by the fact that data is collected in two separate settlements at two different times. This means that, though average winter and summer concentrations for specific PM types are ascertained and ultimately used for comparative purposes, the years in which the data were collected do not correspond entirely. In fact, only Summer/ Spring 2015 represents a time during which the data corresponds to a degree (i.e. data were collected in both KwaDela and KwaZamokuhle during this time). This means that any larger scale influences that might have determined ambient or indoor concentrations during the sampling campaign in KwaDela in a given year will not have been present in KwaZamokuhle and vice versa.

Any studies that deal with people are governed by large complexities. Large assumptions are being made that survey results are a true reflection of reality, though they might be subjective at times. Additionally, when individuals handle personal monitoring equipment (SidePak or GPS monitors), it is assumed that these are being worn at all times and by the same individual who consented to wearing them. An immediate limitation is that the personal PM measurements taken in KwaDela represent only measurements taken during the day hours and not at night, and so "total" exposure is a relative term. Paired GPS and personal PM data are not continuous. This study could be meaningfully built upon by:

- measuring simultaneous ambient, indoor and personal PM concentrations of the same size fractions to allow for a more direct relationship comparison
- calculating and measuring infiltration rates to better understand how ambient air quality affects indoor air quality and vice versa
- adding detailed time-activity journals at an individual level to even better understand and dissect what determines total personal exposure. This would help determine to what degree even personal habits such as cleaning/ sweeping or smoking contribute to indoor PM exposure as compared to indoor burning activities
- taking GPS tracking measurements in KwaZamokuhle as well, to see if the micro-environments identified in this study in KwaDela correspond with those that would be identified in KwaZamokuhle
- taking Personal PM- and GPS measurements continuously to ensure a full picture of personal exposure is painted

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This chapter has outlined the methods used to achieve the objectives of this study. Main data collection methods that were used were 1) continuous ambient, indoor and personal PM monitoring and 2) collection of survey data. Real-time personal GPS data was also collected. Data were then analysed by means of appropriate time-averaging exercises (hourly averages were ascertained for diurnal time-series graphs and daily average concentrations were ascertained to compare concentrations with existing NAAQS). Box plots were created to compare mean and median daily

average and maximum concentrations at a community level. *Cases* were identified where data were simultaneously available for ambient, indoor and personal PM measurements, which enabled the direct comparison between these measurements at a household and at a community level. Finally, real-time PM and GPS measurements were paired to ascertain personal exposure and potential inhalation doses of an individual in KwaDela. The next section represents the first results and discussion chapter, where results are presented and interpreted.

Chapter 4 Characterising Particulate Matter Concentrations

In this first results and discussion chapter, the first objective of the study is addressed in full as PM concentrations in KwaDela and KwaZamokuhle are characterised. Daily average ambient, indoor and personal PM concentrations measured in KwaDela and KwaZamokuhle are compared and contrasted with each other across various seasons. Reasons for concentration variability within and between the communities are outlined and reference is made to existing literature where considered appropriate. Hourly average data are shown by means of diurnal concentration patterns. Objective two of the study, which seeks to better understand relationships between ambient, indoor and personal PM concentration is touched upon here, but further elaborated upon in a subsequent chapter.

4.1 Spatial and temporal variability of particulate matter

Ambient, indoor and personal air quality in KwaDela and KwaZamokuhle was confirmed to be unacceptably poor, particularly in the colder months of the year. NAAQS exceedances were found in both communities, but overall air pollution levels in KwaZamokuhle were higher than in KwaDela, and this in summer and in winter months.

4.1.1 Ambient particulate matter concentrations

Ambient daily average winter PM_{10} concentrations were found to be twice as high as summer concentrations in KwaDela and KwaZamokuhle, respectively and 1.7 times higher in winter than in spring in KwaZamokuhle (Table 4.1 and Figure 4.1). Similarly, ambient daily average winter $PM_{2.5}$ concentrations were found to be on average 2.1 and 1.7 times higher than summer concentrations in KwaDela and KwaZamokuhle, respectively and 2.1 times higher than spring concentrations in KwaZamokuhle (Table 4.**2** and Figure 4.2). The variation of daily averages around the respective PM type mean values was generally high, however, it was higher in spring than in summer, and highest in winter, this trend was apparent in both KwaDela and in KwaZamokuhle.

Figure 4.1. Daily average ambient PM_{10} concentrations (µg/m³) in KwaDela and KwaZamokuhle across the seasons

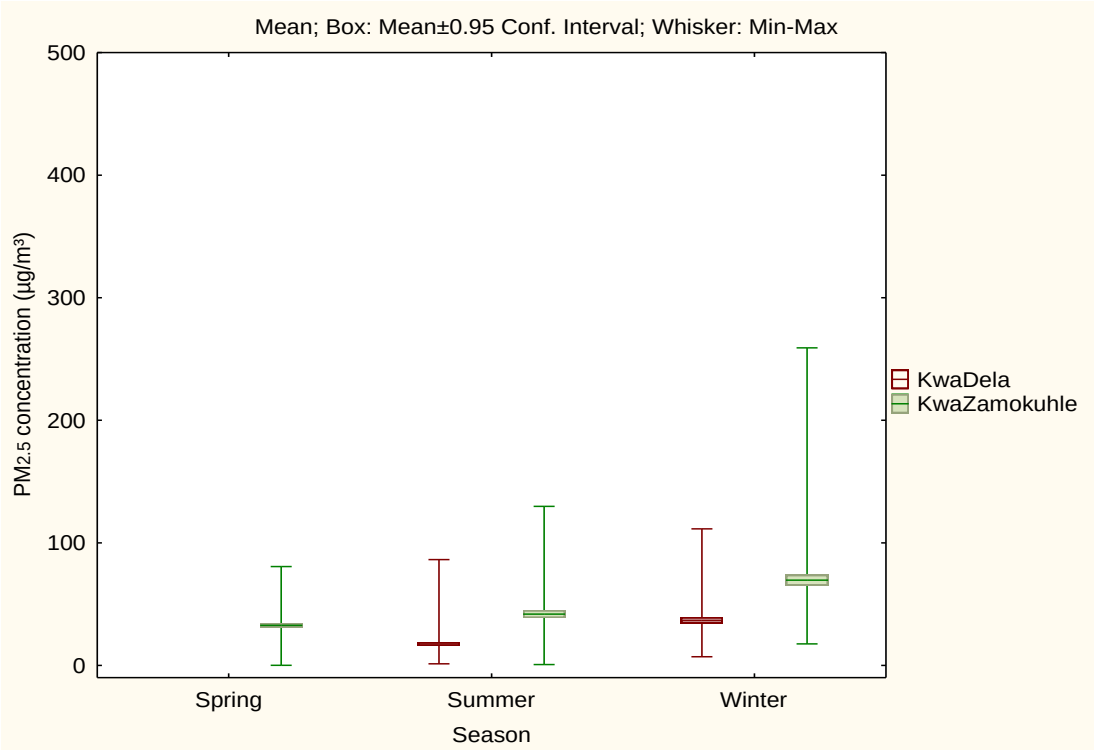


Figure 4.2. Daily average ambient $PM_{2.5}$ concentrations (µg/m³) in KwaDela and KwaZamokuhle across the seasons

When comparing PM concentrations between the two communities, daily average PM_{10} concentrations in KwaZamokuhle were found to be on average 1.2 times higher than the concentrations measured in KwaDela in both summer and winter (Figure 4.1 and Table 4.1). Summer daily average $PM_{2.5}$ concentrations were found to be on average 2.4 times higher in KwaZamokuhle than in KwaDela. In winter, PM concentrations with a diameter of less than 2.5 micrometres were found to be on average 1.9 times higher in KwaZamokuhle than in KwaDela (Figure 4.2).

Table 4.1. Seasonal characteristics (daily mean±S.D.) of ambient PM_{10} concentrations (µg/m³) in KwaDela and KwaZamokuhle

KwaDela	**Winter 2013**	**Summer 2014**	**Winter 2014**	**Summer 2015**	**Average Winter**	**Average Summer**
AMS	96.7±34.77	51.2±16.8	101.1±28.3	55.1±11.5	99.2±33.2	52.1±15.3
KD-E2-SW	95.7±79.2	22.4±15.9	47.0±19.1	21.5±11.3	65.9±60.5	22.7±14.4
Average	99.9±46.3	39.9±20.3	74.7±38.1	44.3±19.9	87.5±47.3	42.9±20.3
	Spring 2015		**Summer 2016**		**Winter 2016**	
KwaZamokuhle	61.2±31.0		52.6±23.6		103.6±31.7	

Table 4.2. Seasonal characteristics (daily mean±S.D.) of ambient $PM_{2.5}$ concentrations (µg/m³) in KwaDela and KwaZamokuhle

KwaDela	**Winter 2013**	**Summer 2014**	**Winter 2014**	**Summer 2015**	**Average Winter**	**Average Summer**
AMS	34.0±11.2	19.1±11.9	29.3±8.7	17.9±3.8	31.4±9.5	18.3±7.8
KD-E1-NW	40.3±16.5	15.5±8.5	53.7±36.2	18.0±25.7	44.8±32.8	16.7±16.5
Average	36.9±13.8	18.1±14.6	37.2±19.2	17.1±10.2	36.3±22.2	17.6±12.4
KwaZamokuhle	**Spring 2015**		**Summer 2016**		**Winter 2016**	
AMS	24.9±12.7		24.4±13.5		55.4±19.4	
KZ-E1-N	33.2±7.5		37.4±13.6		57.9±13.2	
KZ-E2-NW	30.3±8.4		33.7±8.7		NA	
KZ-E3-W	42.3±16.8		38.2±7.9		67.2±19.7	
KZ-E4-SE	38.1±10.7		69.3±28.7		108.7±44.3	
Average	32.6±13.5		42.2±24.8		69.6±32.5	

When considering compliance with the NAAQS, the daily average ambient measurements for PM_{10} and $PM_{2.5}$ surpassed the allowed frequency of exceedances of the respective limit value (4) at every monitoring site during all winter campaigns in both communities, except for at one site (KD-E2-SW) in KwaDela in winter 2014 (Table 4.3 and Table 4.4). In summer, the allowed frequency of exceedances was surpassed for PM_{10} and $PM_{2.5}$ in KwaDela in summer 2014 at the ambient monitoring station only, and for every

PM type measurement in Summer 2016 in KwaZamokuhle, except for the $PM_{2.5}$ at KZ-E3-W. In spring 2015 in KwaZamokuhle, the allowed frequency of exceedances was surpassed at every ambient monitoring site except for one (KZ-E4-SE) monitoring site.

On average, 2% and 4% of the PM_{10} and $PM_{2.5}$ daily averages in summer and 59% and 34% of the PM_{10} and $PM_{2.5}$ daily averages in winter, respectively were found to be above the NAAQS limit in KwaDela. In KwaZamokule, 32%, 13% and 86% of the PM_{10} daily averages measured in spring, summer and winter, respectively were found to lie over the NAAQS limit value. $PM_{2.5}$ daily averages were found to be above the NAAQS limit value 23%, 40% and 91% of the time in spring, summer and winter, respectively.

Ambient air quality in the winter months, particularly in KwaZamokuhle, was characterised by daily average PM concentrations that exceeded the NAAQS most of the time. Daily average $PM_{2.5}$ concentrations were on average higher in KwaZamokuhle than they were in KwaDela, and this particularly in winter. This could be attributed to the prevalence of more source contributors of the smaller size fraction particles into the ambient air in KwaZamokuhle, but this is unpacked further into the dissertation.

Table 4.3. Number of NAAQS limit value exceedances per season per community for PM_{10} (total number of daily averages)

KwaDela	**Winter 2013**	**Summer 2014**	**Winter 2014**	**Summer 2015**
AMS	41(50)	6(78)	22(29)	0(29)
KD-E2-SW	8(12)	0(23)	3(31)	0(25)
KwaZamokuhle	**Spring 2015**	**Summer 2016**		**Winter 2016**
AMS	23(73)	7(52)		51(59)

*Daily limit value = 75 µg/m³; Allowed frequency of exceedances = 4 per annum

Table 4.4. Number of NAAQS limit value exceedances per season per community for $PM_{2.5}$ (total number of daily averages)

KwaDela	**Winter 2013**	**Summer 2014**	**Winter 2014**	**Summer 2015**
AMS	17(62)	4(46)	8(68)	0(61)
KD-E2-SW	10(27)	0(55)	25(42)	2(28)
KwaZamokuhle	**Spring 2015**	**Summer 2016**		**Winter 2016**
AMS	8(84)	8(46)		45(59)
KZ-E1-N	0(53)	19(55)		46(49)
KZ-E2-NW	10(63)	6(37)		NA
KZ-E3-W	30(60)	3(7)		41(43)
KZ-E4-SE	13(35)	45(52)		39(39)

*Daily limit value = 40 µg/m³; Allowed frequency of exceedances = 4 per annum

The clearly defined seasonal variability of lower ambient PM concentrations in summer and higher PM concentrations in winter, as is apparent in both KwaDela and KwaZamokuhle, is influenced by numerous factors:

In winter, the Mpumalanga Highveld is characterised by high atmospheric stability, clear skies and low wind speeds associated with high pressure systems and circulation is generally anticyclonic (Tyson, 1988). In summer, less stable conditions, dominated by easterly circulation patterns with high rainfall and high wind speeds, prevail (Fourie *et al.*, 2008). Considering such macro-scale weather conditions, the dry winter climate prevailing on the Highveld leads to increased particle load in the atmosphere and decreased atmospheric mixing. A dry winter climate in the Highveld contributes to the load of suspended dust particles in the atmosphere in winter in particular (Jury, 2017).

Source apportionment studies that were conducted as part of KwaDela and KwaZamokuhle's air quality offset pilot studies, indicated that soil dust contributed a small fraction of the aerosol loading when considering the coarse and fine fraction (6.2% and 5.5%, respectively) in KwaDela (Sasol, 2015). Road dust contributed 14% of the coarse fraction aerosol loading in KwaZamokuhle, and road and wind-blown dust contributed 12% of the fine fraction aerosol loading in winter (Eskom, 2017). Significantly, in KwaZamokuhle, source apportionment results showed that aeolian dust, which represents dust from surface sediments and soils, contributed 28% to the coarse fraction of PM in winter. Conversely, in climatic regions where summer-rainfall patterns prevail, such as the Mpumalanga Highveld, the contribution of such dust particles is expected to be correspondingly lower, as increased humidity and rainfall suppresses the entrainment of dust into the atmosphere. Source apportionment results indicated that road and wind-blown dust contributed up to 43 % to the course fraction and 16% to the fine fraction in summer in KwaZamokuhle. Though this might seem contradictory, it makes sense that wind-blown dust contributes greatly to aerosol loading in summer relative to other source contributors, as coal combustion, which contributes the most to the aerosol loading in winter, contributes a substantially lower fraction. Observed low wind speeds in winter in KwaZamokuhle in particular, represent a further large-scale climatic condition that exacerbates high concentrations of locally emitted PM. Winds contribute significantly to the dispersion and dilution of emissions, thus when low wind speeds prevail, high pollutant concentrations are measured.

The South African Highveld is well known for the formation of well-developed inversion layers that typically form during the night and persist until later morning (Garstang *et al.,* 1996; Freiman & Tyson, 2000; Hirsikko *et al.,* 2012). Most of the emissions are released from sources located near the earth's surface up to a few hundred meters. The existence of frequent inversion layers forces the diffusion and transport of pollutants to take place in the lower parts of the atmosphere for prolonged periods of time causing high PM concentrations (Fourie *et al.,* 2008). In winter in particular, this effect is intensified because higher amounts of particles are trapped under the inversion layer and so emissions from domestic burning practices remain stuck close to the earth's surface (Jury, 2017).

Finally, local activities on the ground contribute greatly to the seasonal variability of ambient PM concentrations. In KwaDela and KwaZamokuhle the high PM concentrations in winter and the reduced PM concentrations in summer are directly proportional to the amount of domestic burning and heating activities that take place during those seasons. In KwaDela for instance, it was found that households used on average 216 kg of coal for heating and cooking activities during an average winter month compared to 117 kg of coal in an average summer month (Sasol, 2015). Consequently, burning increased amounts of coal leads to increased suspended particles in the atmosphere in winter months.

Source apportionment data supports the above statements as it was found that the biggest contribution to the aerosol loading in both communities in winter was from coal combustion: In KwaZamokuhle, in winter, 38% of the course fraction and 52% of the fine fraction could be attributed to coal combustion. Similarly, in KwaDela, 56% and 61% of the fine and course fraction, respectively could be attributed to coal combustion related sources (Sasol, 2015). This can be strongly contrasted to 15% and 3% contribution to the course and fine fraction in summer in KwaZamokule (Eskom, 2017).

The prevalence of spring data in KwaZamokuhle allows for interesting seasonal transition observations, where the changeover from winter to summer becomes clear and predominantly cold days slowly give way to, on average, warmer temperatures. Warmer days presumably lead to less frequent and prolonged heating and cooking activities at a household-level, and with that, lower PM concentrations are evident.

KwaDela and KwaZamokuhle lie in relative close proximity to each other geographically and are thus governed by the same macro-scale meteorological cycles described above. Therefore, starkly contrasting

differences in air pollution levels between the communities can more than likely be attributed to local-scale phenomena, more specifically to anthropogenic sources. It should not be discounted however, because data collected for the different communities were not collected in the same years, that though one would expect similar large-scale seasonal meteorological trends to remain consistent, it could be the case that winter 2013/14 (KwaDela) and winter 2016 (KwaZamokuhle) were in fact characterised by different local meteorological conditions. Consequently, it was noted that stronger westerly waves and more severe cold front conditions, contributed to the observed increased PM concentrations in KwaZamokuhle. Considering the average meteorological data (Table 3.2 and Table 3.3), average minimum temperatures in KwaZamokuhle in winter 2016 were lower than those measured in winter 2013 and 2014 in KwaDela, which could point to an overall perceived colder winter in 2016 and corresponding increased solid fuel burning activities for heating purposes.

KwaZamokuhle is a larger community when compared to KwaDela, with a population about five (5) times higher. A logical conclusion to draw from this, would be that a larger number of households results in a proportionally larger number of coal burning households. However, taking into account the socio-economic complexities that persist in different communities, it is inappropriate to draw over-simplistic conclusions.

According to Statistics South Africa (Stats SA, 2012b), proportionately, a higher percentage of households make use of coal for cooking and heating activities in KwaDela than in KwaZamokuhle (Table 3.1). When delving further into demographic specifics, one can see that a higher proportion of households is electrified in KwaDela (97%) than in KwaZamokuhle (89%). It is often assumed that access to electricity and the consequent use of electrical appliances on the one hand and the use of coal for heating and cooking purposes on the other hand are mutually exclusive (Stats SA, 2012a). However, high unemployment rates and low incomes force households to rely on cheaper, dirtier fuels, and so, though houses may be electrified, coal is still relied on as a main domestic energy source (Stats SA, 2012a). There are more people who live below the poverty line in KwaZamokuhle than in KwaDela, pointing to a higher proportion of people who would have to rely on coal for cooking and heating as it is the cheaper fuel option, even if electricity is available (Stats SA, 2012b).

4.1.2 Spatial and seasonal trends of indoor and personal particulate matter concentrations within and between two communities

When comparing the overall daily mean indoor PM concentrations across the seasons within each community, winter PM_4 concentrations in the indoor environment were shown to be on average 1.7 and 3.0 times higher in winter than in summer in KwaDela and KwaZamokuhle, respectively (Figure 4.3 and Table 4.5). Personal PM_4 concentrations were on average 1.9 and 3.1 times higher in winter than they were in summer in KwaDela and KwaZamokuhle (Figure 4.4 and Table 4.5). The variation of daily averages around the mean values was higher in spring than in summer, and highest in winter; it is notable that the standard deviation around the arithmetic mean was on average higher in the indoor environment than it was in the ambient environment. Speculatively. this high variability could be attributed to (i) the number of burning activities that take place in a specific household on a given day; (ii) the number of times and the way in which the stove is refuelled; (iii) the different types of stoves that are used, and even (iv) how these factors change across the seasons.

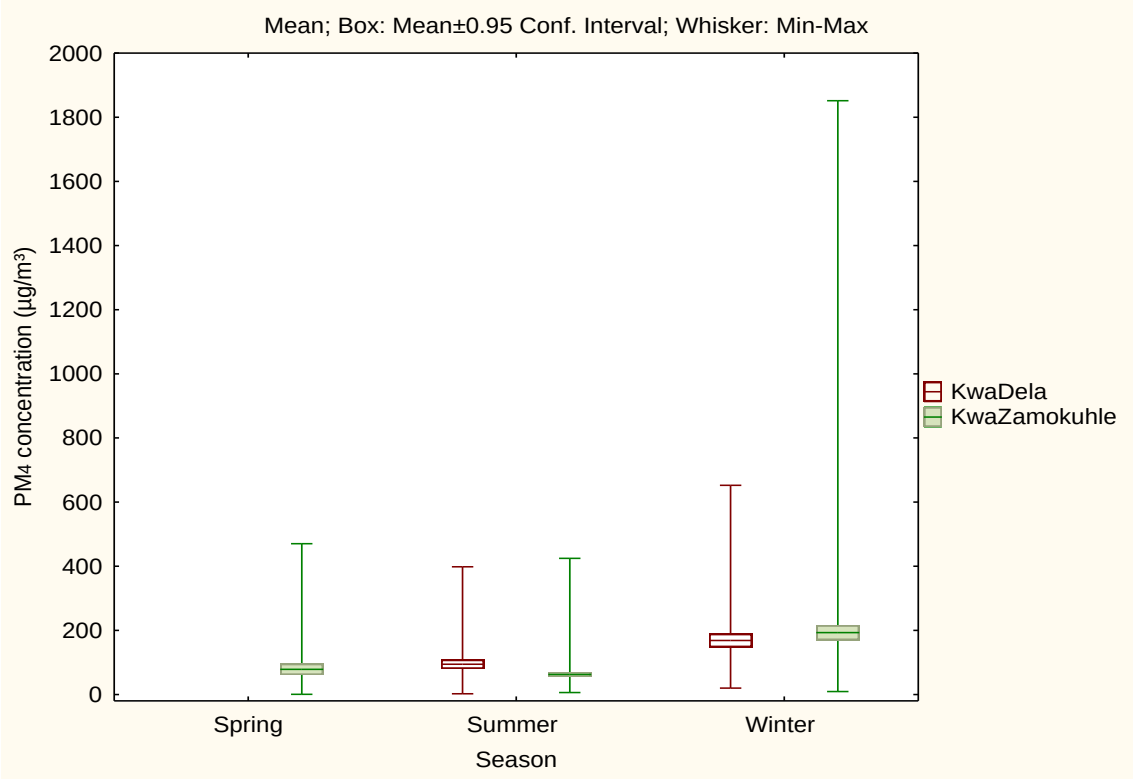


Figure 4.3. Daily average indoor PM_4 concentrations (µg/m³) in KwaDela and KwaZamokuhle across the seasons

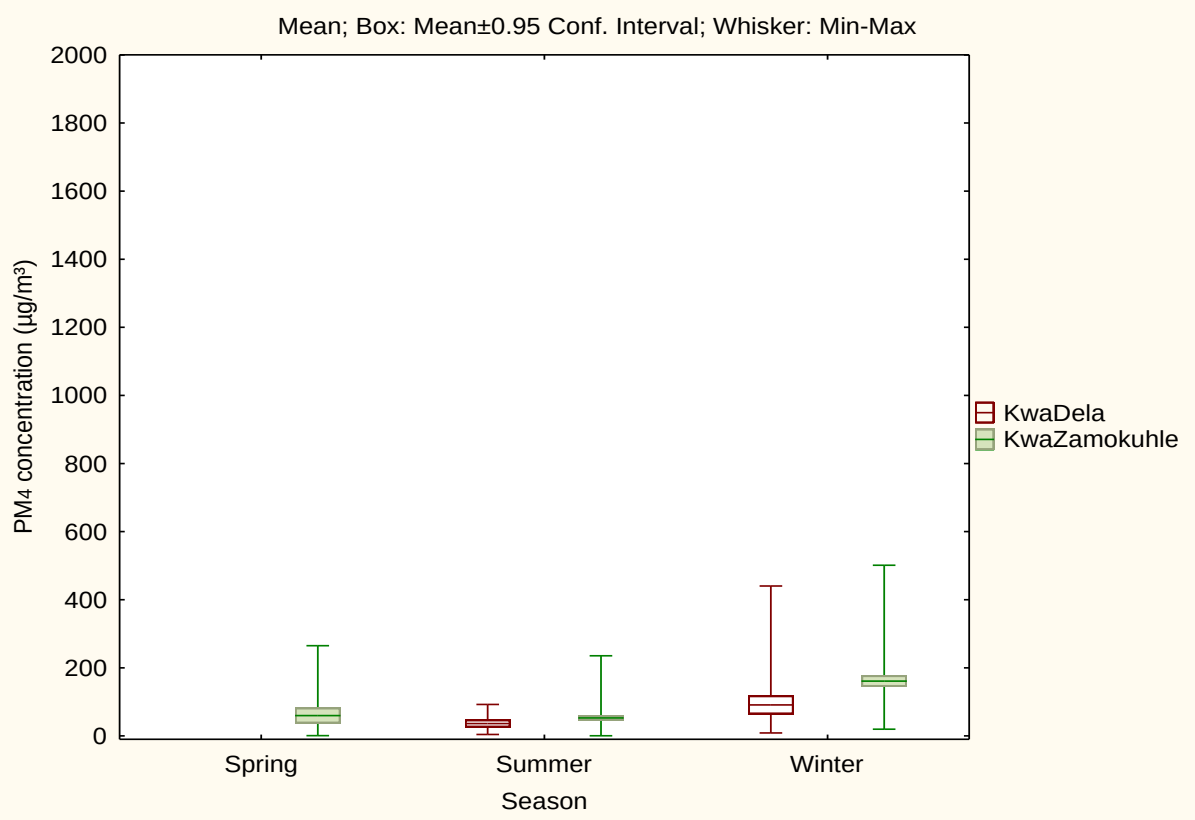


Figure 4.4. Daily average personal PM_4 concentrations (µg/m³) in KwaDela and KwaZamokuhle across the seasons

On average, indoor PM_4 concentrations in KwaDela were 1.5 times the concentrations measured in KwaZamokuhle in summer and the concentrations in KwaZamokuhle were 1.2 times the concentrations measured in KwaDela in winter. Personal PM_4 concentrations in KwaZamokuhle, were on average 0.7 and 2.3 times the concentrations measured in KwaDela in summer and in winter (Table 4.5).

Table 4.5. Seasonal characteristics (daily mean±S.D.) of indoor and personal PM concentrations (µg/m³) in KwaDela and KwaZamokuhle

KwaDela	PM Type	Winter 2013	Summer 2014	Winter 2014	Summer 2015	Average Winter	Average Summer
Indoor	**PM4**	183.6±144.9	62.4±65.2	149.1±96.0	138.2±89.4	166.0±137.4	99.3±99.7
Personal	**PM4**	92.0±97.1	27.4±17.5	47.2±23.1	47.7±21.9	69.6±106.1	37.7±178.4
KwaZa-mokuhle	**PM Type**	**Spring 2015**		**Summer 2016**		**Winter 2016**	
Indoor	**PM4**	78.5±84.4		65.1±50.7		192.9±181.2	
Personal	**PM4**	58.3±68.3		52.9±44.6		161.1±103.7	

Though indoor PM guideline limits are soon to be published, no regulatory indoor or personal air quality standards exist in the Republic of South Africa. There is also no standard which limits particles with a diameter that is generally four (4) micrometres and smaller. For this reason, daily average indoor and personal PM_4 concentrations, as measured in the sampling campaigns used for this study, cannot be directly compared to a limit value to ascertain whether or not PM concentrations in the indoor environment are compliant with prescriptive legislation. Nonetheless, PM with a diameter of <2.5 µm represents a subset of PM with a diameter of four (4) µm, which in turn, represents a subset of PM with a diameter of ten (10) µm. Measured daily averages will thus be roughly contextualised by considering the daily PM_{10} NAAQS, as this would represent a conservative assessment of the exceedances of the PM standards.

In KwaZamokuhle, indoor and personal daily average PM_4 concentrations were found to lie above the PM_{10} NAAQS of 75µg/m^3 39%, 28% and 85% of the time in spring, summer and winter, respectively. Personal PM_4 daily average concentrations were above the PM_{10} limit 27%, 22% and 79% of the time in spring, summer and winter. In KwaDela, personal and indoor daily average PM_4 concentrations were above the PM_{10} limit value 35% and 75% of the time in winter and 11% and 45% of the time in summer.

Indoor and personal PM concentrations measured during the KwaDela and KwaZamokuhle sampling campaigns were highly variable in space and time and most notably, measured concentrations even reached into the mg/m^3 range. Complex larger and smaller scale seasonal factors that trigger the variability of these concentrations would mostly be related to what negatively influences the thermal comfort within a household, such as low ambient temperatures and high precipitation- and wind speeds. Other large-scale temporal factors influencing this variability can be attributed to the time of day, as this greatly governs burning times in a home (discussed in more detail in Chapter 5 below). More local-scale, socio-economic factors that can contribute to the inhomogeneous temporal and spatial distribution of anthropogenic emissions of PM concentrations in different households are: income levels, energy-/ fuel type and availability, how this fuel is burnt and what stove it is used, cultural preferences, social class, the number of the household inhabitants, location of the household itself and the structure and the integrity of the house (Scorgie *et al.*, 2003; Kimemia & Annegarn, 2011; Kimemia *et al.*, 2016; Masekameni, 2017). This list is not exhaustive but does give an indication of the complexity of the problem.

A study conducted to better understand what contributing factors govern the variability of domestic burning habits on the South African Highveld, with a particular focus on KwaDela, showed that about 98% of the individuals who participated in the fuel use observation in KwaDela use coal, wood, dung and paper in a single burning event, and not all did this in the same manner (Nkosi *et al.,* 2017). It was also shown that the appliances used to burn the coal varied tremendously in shape, form, quality and age, some stoves being as old as 25 years. The majority of the stoves used were broken and leaks were also apparent, allowing smoke to escape from the combustion chamber and to enter the household. Another way in which smoke enters the house is when the chimney attached to the stove is either not fully extended through the roof, or is not structurally intact (Nkosi *et al.,* 2017). The area within which coal burning takes place differs from household to household: many stoves are located within the kitchen of the household; however, some are also located in the living room, or in a different room entirely (sometimes this room would be an external extension to an existing house structure) (Nkosi *et al.,* 2017). Burning practices in low-income communities in South Africa are mostly focused on cooking activities in the warmer months and include heating activities in the colder months. Coal is preferred, even in households that have access to an electricity supply due to its availability and its affordability, and due to its multi-functional nature (supports cooking, heating and lighting functions) (Scorgie *et al.,* 2003).

High indoor PM_4 concentrations related to burning activities (not taking into account other sources of PM in the indoor environment, such as smoking) are mostly a function of combustion activities that take place directly inside the household but can also be attributed to infiltration of external emissions stemming from the ambient environment. How much air pollution infiltrates into a household from the ambient environment (stemming from burning and other non-burning related sources) depends on the proximity of the external source to the household, the prevailing weather conditions, the structural intactness of the household in question (i.e. how airtight it is), and whether or not windows and doors are open to let in the external emissions (Meng *et al.,* 2005). Outdoor particles can enter indoor environments by convective flow (e.g. through an open window) or by diffusional flow (i.e. infiltration) and through cracks and fissures in the barrier of the building envelope (Meng *et al.,* 2005; Cao *et al.,* 2012). Contributions of outdoor sources to indoor $PM_{2.5}$ concentrations have been estimated to range between 23–67% in low-income communities (Meng *et al.,* 2005; Cao *et al.,* 2012). This has not been estimated in an average South African low-income household.

Though it is easy to say that the overall variability in indoor PM concentrations measured in KwaDela and KwaZamokuhle is influenced by a combination of a wide range of large-scale and local-scale factors as described above, it is only possible to really understand what influences indoor and personal exposure to PM concentrations if one delves into specific households individually and tries to better understand the specific parameters that could influence the air quality that is breathed in that specific household itself. This approach is touched upon in Chapter 5 below.

The variability of personal PM concentrations, i.e. the concentrations measured by the SidePak device worn by a select number of individuals within KwaDela and KwaZamokuhle for short periods of time is even more complex to unravel as these concentrations are measured in various locations as the individual wearing the monitor moves through space and time and sources to which an individual is exposed are present in the indoor and the ambient environment. Generally spoken, personal PM_4 concentrations measured across these study campaigns will have been influenced by the same macro- and micro- scale factors that have been outlined to influence ambient and indoor PM concentrations in the paragraphs above, as they essentially represent an amalgamation of ambient and non-ambient components (Wilson *et al.*, 2000). This means that, a person exposed to particulates stemming from indoor and ambient sources in winter months, is bound to be exposed to higher average PM concentrations regardless of which micro-environment the individual finds himself/herself in, than the same individual would be exposed to in summer months in the same micro-environments.

A one-individual case study outlined in Chapter 5 of this thesis expands on the complexities of personal PM exposure by considering a one-individual case study in KwaDela.

4.1.3 Indoor and personal hourly maximum particulate matter concentrations

Average hourly maximum winter PM_4 concentrations in the indoor environment were on average 1.1 and 3.2 times higher in winter than in summer in KwaDela and KwaZamokuhle, respectively. Personal average hourly maximum PM_4 concentrations were on average 2.2 and 2.1 times higher in winter than they were in summer in KwaDela and KwaZamokuhle (Figure 4.5 and Figure 4.6).

In KwaZamokuhle, average winter indoor hourly maximum PM_4 concentrations were 2.3 times higher than in spring and average winter personal maximum PM_4 concentrations were 5.2 times higher than in spring. For the sake of this comparison, the highest hourly average value for each day was ascertained and then averaged for the days for which measurements were conducted.

Indoor and personal hourly maximum PM_4 concentrations are important indicators of extreme exposure events (Table 4.6). People spend most of their time in the indoor environment (particularly in the colder months), and consequently the health of the individuals in the indoor environment is likely to be affected by such acute exposure events during fire ignition activities for instance (Smith & Mehta, 2003). People living in KwaDela and KwaZamokuhle are exposed to high levels of PM concentrations at both longer and shorter durations resulting in increased risk of both acute (short-term) and chronic (long-term) health effects (Bundi, 2004).

While it is incredibly useful to compare averaged PM concentrations for potential compliance against longer-term air pollution standards, or to assess chronic exposures, this does not offer a reliable means of assessing short-term, extreme concentrations and acute exposures, and hence maximum values need to be considered (Briggs *et al.,* 2000). Highest indoor and personal exposure events are most likely to be experienced by those individuals who use coal stoves in poorly ventilated environments, or who are in close proximity to them (typically women and children) (Chen & Smith, 1991; Fullerton *et al.,* 2008*).* Personal exposure events however are not limited to the indoor environment and can also be experienced in the ambient environment, though these maximum exposure events are less likely to be as extreme as those experienced indoors, as particles are more likely to diffuse. This becomes clear when considering the differences between the average maximum concentrations measured in the indoor environment and the average maximum concentrations measured on the personal monitors (Figure 4.5 and Figure 4.6). The general trend of higher average concentrations in both KwaDela and KwaZamokuhle (even of maximum nature) in the winter months is recorded here.

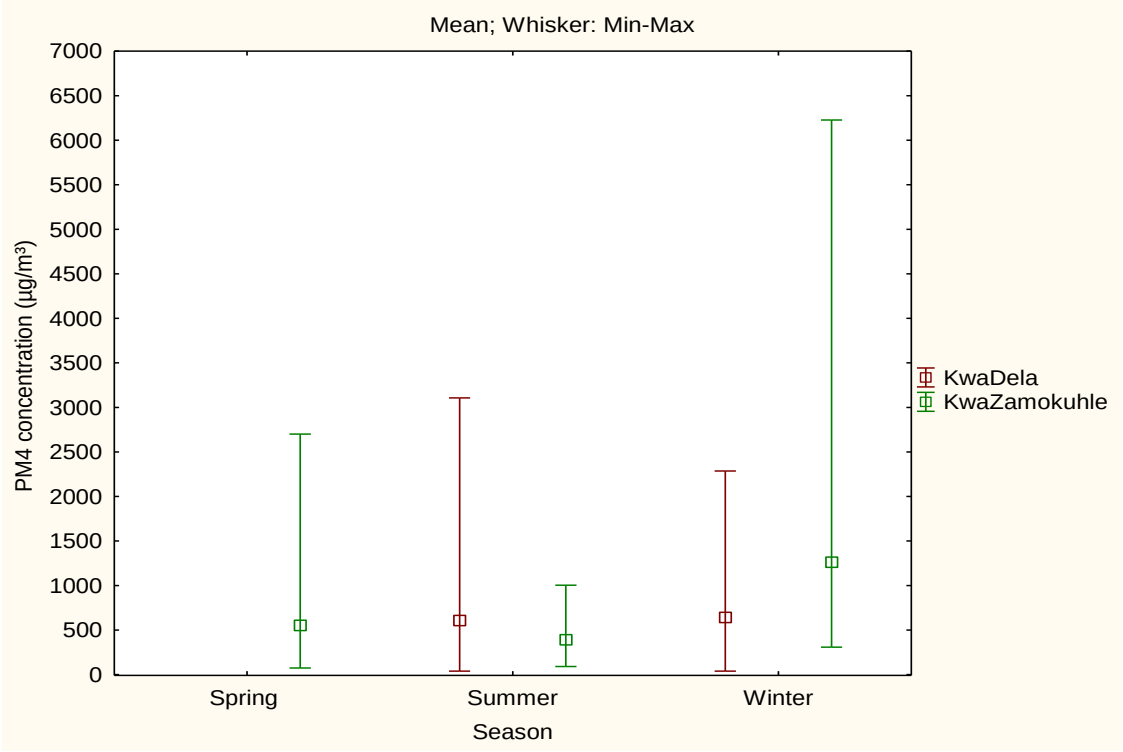


Figure 4.5. Average hourly maximum indoor PM_4 concentrations (µg/m³) in KwaDela and KwaZamokuhle across the seasons

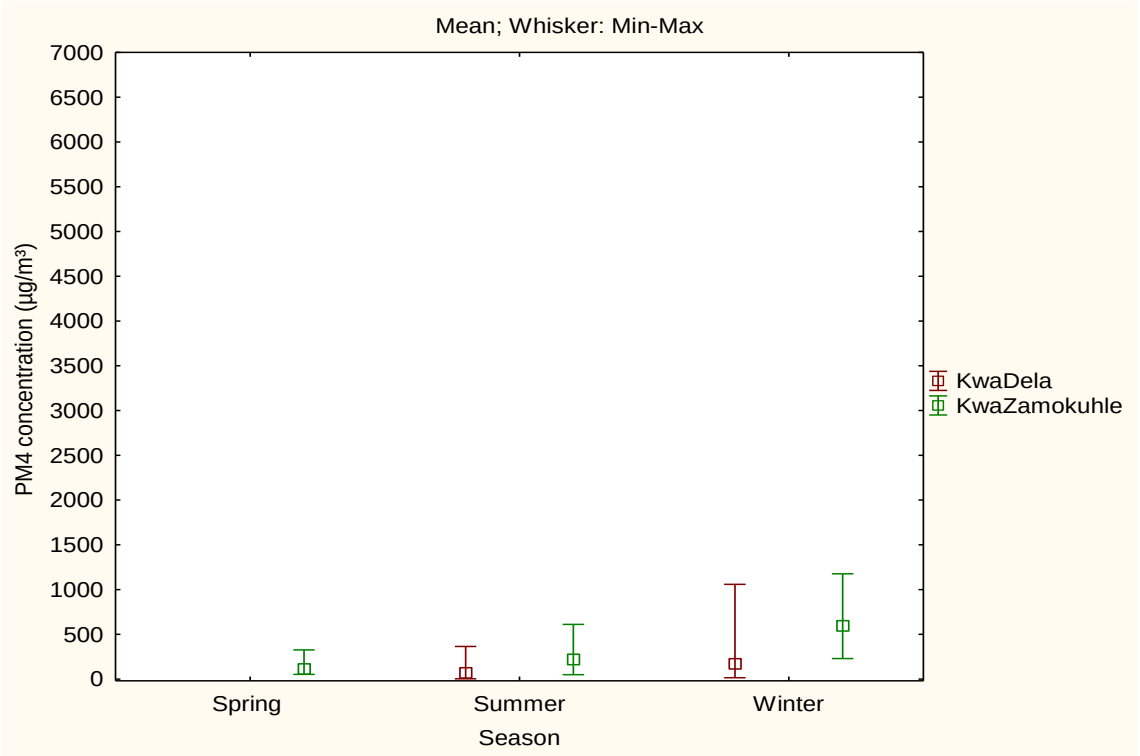


Figure 4.6. Average hourly maximum personal PM_4 concentrations (µg/m³) in KwaDela and KwaZamokuhle across the seasons

Indoor and personal measured hourly maximum PM_4 concentrations were found to be on average 1.9 and 3.9 times higher in KwaZamokuhle than in KwaDela in the winter season. Indoor summer average maximum PM_4 concentrations in KwaDela were 1.5 times the concentrations measured in KwaZamokuhle. Maximum personal concentrations measured in the summer campaigns were found to be on average 3.2 times higher in KwaZamokuhle than in KwaDela.

Table 4.6. Seasonal characteristics (hourly max±S.D.) of indoor and personal PM concentrations (µg/m³) in KwaDela and KwaZamokuhle

KwaDela	PM Type	Winter 2013	Summer 2014	Winter 2014	Summer 2015	Average Winter	Average Summer
Indoor	**PM4**	622.8±731.1	432.7±378.5	675.9±619.2	703.9±902.8	649.4±37.5	568.0±191.3
Personal	**PM4**	224.3±286.4	63.1±61.1	76.0±71.7	72.6±94.3	150.2±104.9	67.8±6.7
KwaZa-mokuhle	**PM Type**	**Spring 2015**		**Winter 2016**		**Summer 2016**	
Indoor	**PM4**	551.2±956.6		1261.1±1773.1		391.2±369.0	
Personal	**PM4**	113.6±96.7		595.3±317.8		220.8±202.2	

4.1.4 Diurnal patterns of ambient, indoor and personal particulate matter concentrations

A pronounced bimodal diurnal pattern was identified when plotting overall hourly average time-series graphs for ambient PM measurements in both KwaDela and KwaZamokuhle (Figure 4.7 and Figure 4.8). Obvious concentration peaks were evident between 5-9 am in the morning and again between 5-9 pm in the late afternoon/ early evening. In some instances, random hourly average peak concentrations were measured during the day (for instance for PM_{10} at KD-E2-SW in KwaDela in winter 2013). Midday peaks were also measured at some of the ambient monitoring sites in winter 2013, winter 2014 and summer 2015 in KwaDela and in summer and winter 2016 in KwaZamokuhle.

Pronounced seasonal differences of ambient hourly average concentrations were observed in both communities with the highest average concentrations typically measured in winter (average concentrations ranged between 30 – 300 µg/m³) and the lowest concentrations generally measured in the summer (ranging between 15 – 100 µg/m³). Winter hourly average concentrations were observed to be higher than summer concentrations in both considered communities, showing correspondence once again between increased suspended particle loads in the atmosphere and larger scale climatic conditions such as low temperatures

and low wind speeds and inversion layers as well as local scale conditions such as increased low-level burning practices at a household level contributing to this difference. Notably, the time of day affects the ambient concentrations that are measured; as such, peak concentrations correspond directly with peak burning times (Oglesby *et al.*, 2000; Huang *et al.*, 2015; Wang *et al.*, 2015). Additionally, PM concentrations are higher when local atmospheric conditions are most stable (i.e. the mornings and the evenings) as concentrations remain largely undiluted. Concentrations are lower when the local atmosphere is unstable and atmospheric mixing takes place and concentrations are diluted (during the day) (Ali *et al.*, 2015).

Surveys that considered burning times during the campaigns in KwaZamokuhle support previous findings that the first peak burning times in the day typically occurred in the early mornings, when individuals commenced their morning routines to start the day, which include cooking and heating water for bathing purposes and space heating in winter (Eskom, 2017; Nkosi, 2017). Daytime burning activities take place for cleaning purposes and occasionally for cooking. Late afternoon and early evening fires are primarily made for cooking-, but also for space heating-, bathing- and socialising purposes and can be made indoors and outside. Late evening fires are made again (including rekindling of existing fires) mostly for space heating, particularly in winter (Ali *et al.*, 2015; Bartington *et al.*, 2017). The highest and most well-defined peaks of PM are typically experienced in the mornings and the evenings. Sporadic peaks do occur during the day but are comparatively low. Hourly average $PM_{2.5}$ concentrations, though following a similar diurnal trend to the hourly average PM_{10} concentrations, typically plotted at lower average concentration values (with the exception of the occasional concentration peak); this makes sense as $PM_{2.5}$ represents a subset of PM_{10} concentrations. The different $PM_{2.5}$ concentrations measured at the various E-Samplers and E-Bams across the communities are a testimony to the spatial distribution of the sampling sites and the high variability of PM concentrations in the ambient environment across the communities. The fact that $PM_{2.5}$ and PM_{10} concentrations do not always follow the exact same diurnal trend can be attributed to different source contributions to that specific size fraction during that time.

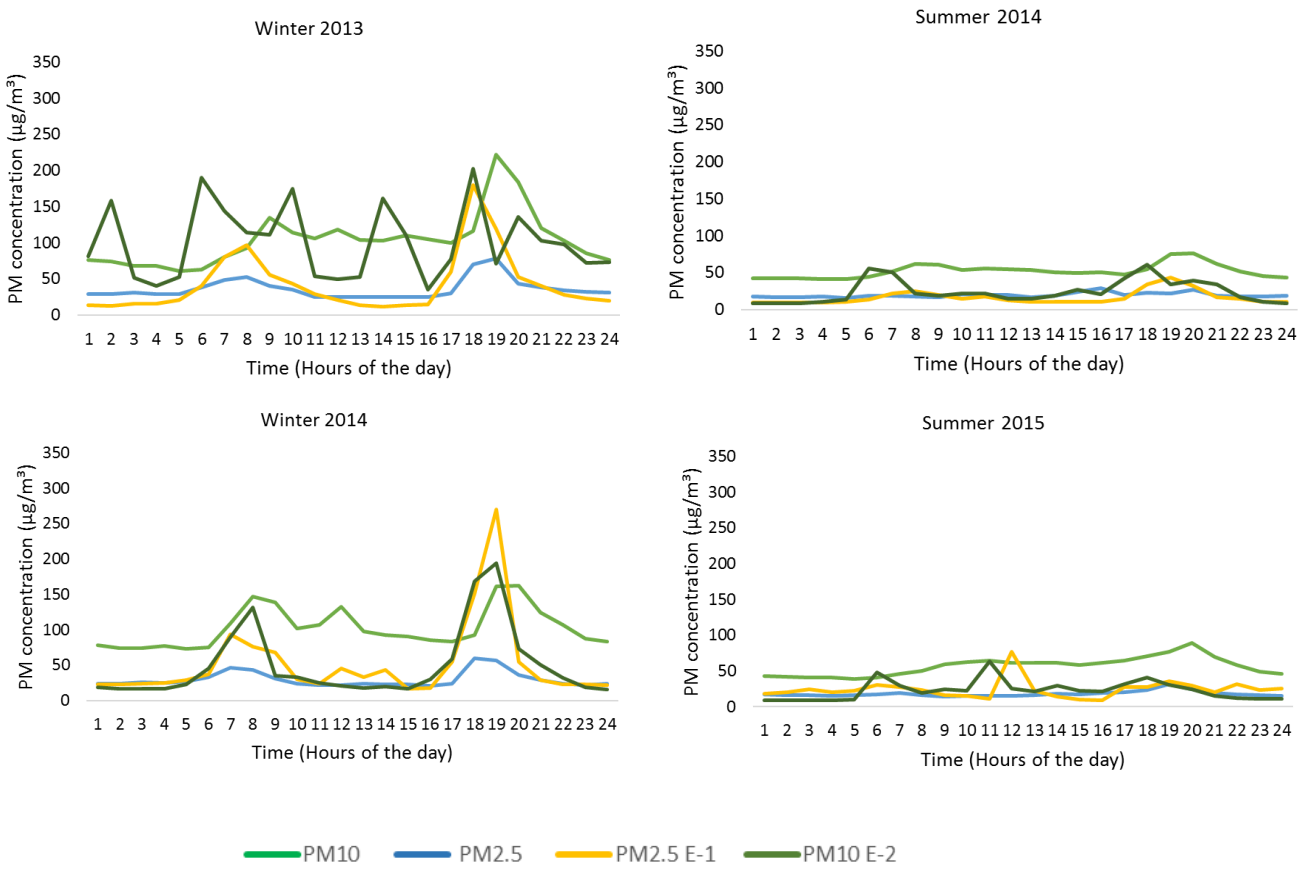
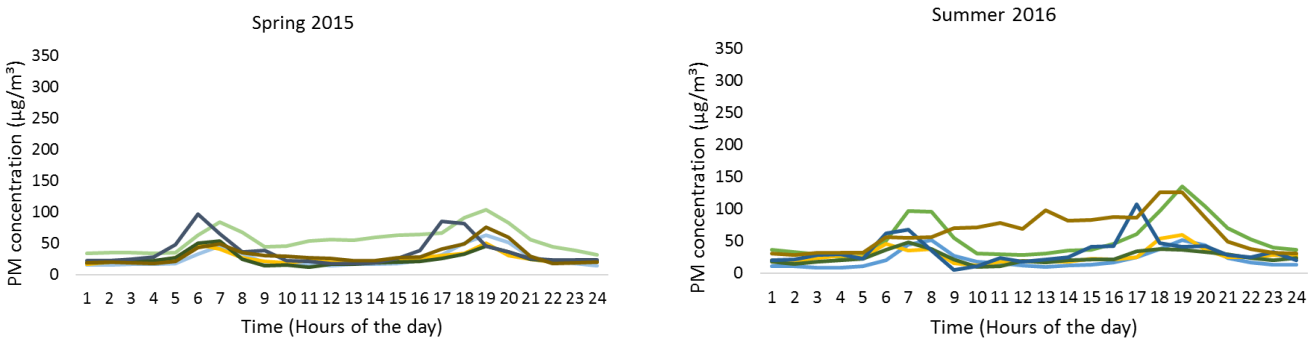


Figure 4.7. Ambient particulate matter diurnal trends (µg/m³) per season in KwaDela



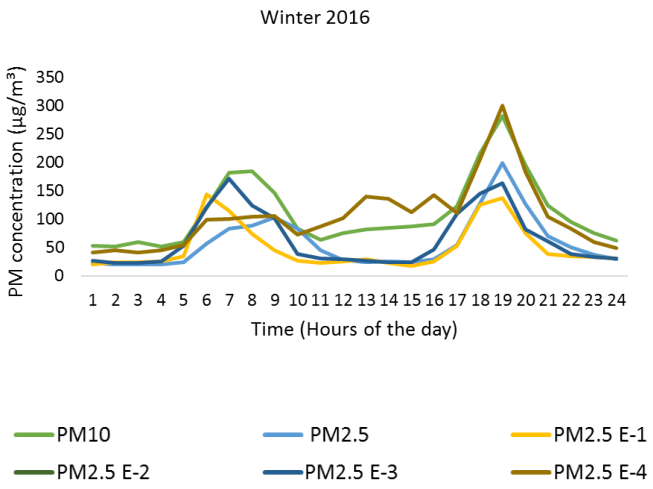


Figure 4.8. Ambient particulate matter diurnal variation (µg/m³) per season in KwaZamokuhle

Similar to the ambient diurnal variation patterns, the indoor PM_4 concentrations showed two distinct peaks, one corresponding to the early hours of the morning (between 4 - 10am) and one corresponding to the early evening hours (typically starting from 5pm, but sometimes starting from as early as 3pm – 9pm), this temporal variation is most attributable to the different burning times in different households (Nkosi *et al.*, 2017) (Figure 4.9 and Figure 4.10). It should be pointed out here that there is a large variability in the burning times at a household level: it is likely that no two houses display the exact same burning patterns in terms of time, duration and even fuel type used. Notably, indoor hourly average concentrations were on average higher than those measured in the ambient environment with hourly average values reaching up to 700 µg/m^3 in winter.

Diurnal variations for indoor and personal PM_4 concentrations were plotted for each sampling campaign for each community (Figure 4.9 and Figure 4.10). Personal measurements taken during the KwaDela sampling campaigns were typically only available during the day hours, leading to gaps in the data during peak hours, whereas personal PM_4 measurements were available for all hours of the day in KwaZamokuhle. Highest hourly personal concentrations were up to twice as high in winter than in summer in both communities, reaching concentrations of up to 800µg/m³.

Congruence between indoor and personal hourly average concentrations was evident across all seasons in both communities and more so in KwaZamokuhle than in KwaDela in the winter months.

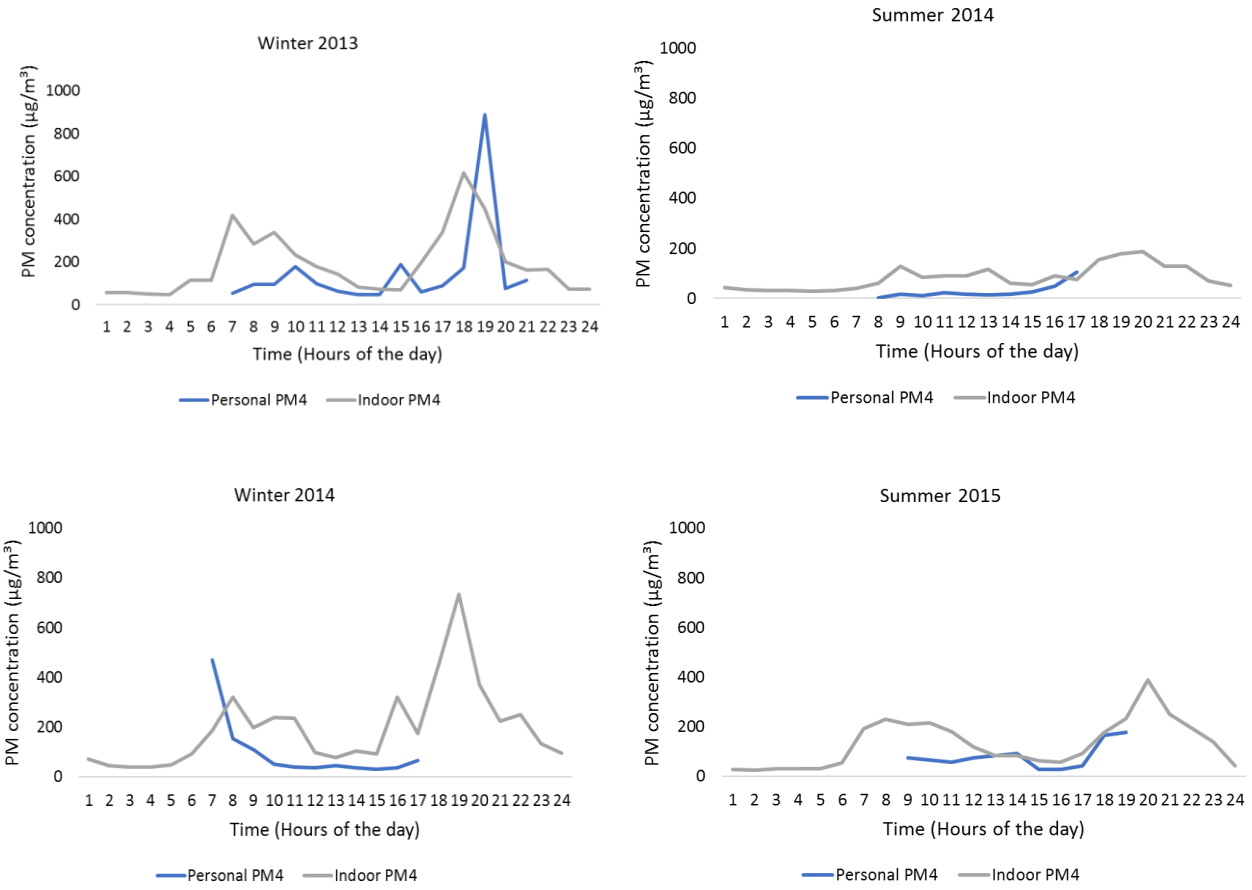
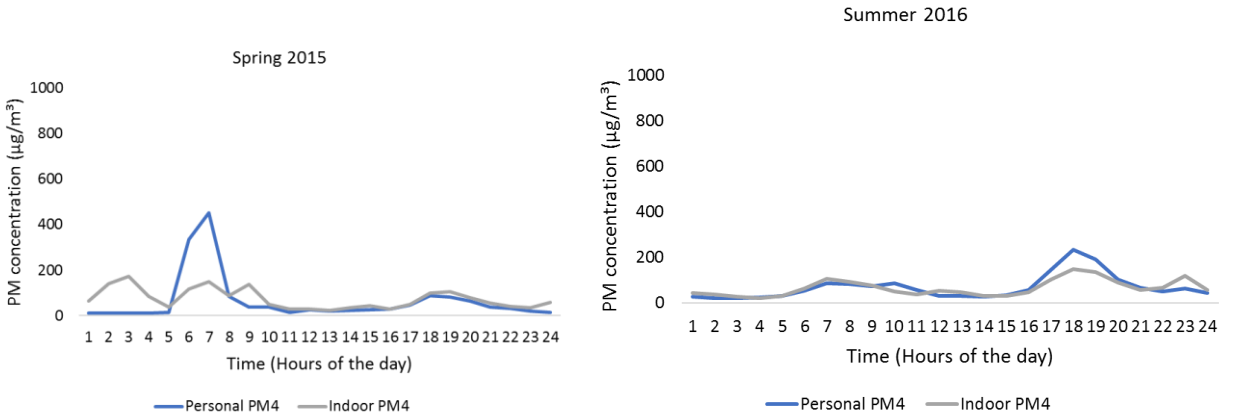


Figure 4.9. Indoor and personal articulate matter diurnal trends (µg/m³) per season in KwaDela



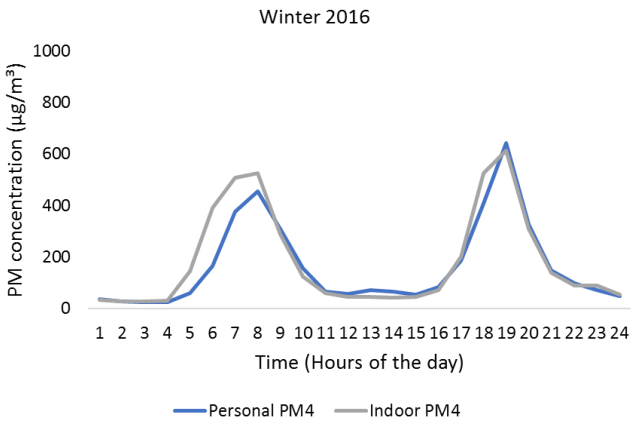


Figure 4.10. Indoor and personal particulate matter diurnal trends (µg/m³) per season in KwaZamokuhle

It should be pointed out that evening concentrations are observed to be the highest peaks measured for ambient and indoor concentrations. This same trend was mostly apparent when considering the personal measurements, though personal PM measurements in winter 2014 in KwaDela and spring 2015 in KwaZamokuhle did not always show the same peaks. This could be attributed to individuals being in close proximity to heat sources besides the ones within their homes. The fact that evenings represent times during which people return from work and burn coal to cook, heat, bath and socialise makes this evening peak plausible. Increased traffic activity on dusty roads should not be discounted as a meaningful contributor to peak PM concentrations in the mornings, when people go to work, and in the afternoon/ evenings when they return (Lozano *et al.*, 2007).

4.1.5 Spatial variability of hourly maximum particulate matter concentrations per *case* per community

In KwaDela and KwaZamokuhle, maximum hourly concentrations measured at a *case* level were generally higher in winter than they were in summer; this applies to all PM types measured (Figure 7.1 - Figure 7.7 in Annexure A). Indoor PM_4 concentrations fairly consistently showed a larger range of hourly maximum concentrations than did ambient concentrations, with a number of extreme values.

At a glance, a high variability of hourly maximum values between the *cases* is evident, pointing to the contribution that spatial factors play in determining the variability of PM concentrations across a community. Highest hourly maximum concentrations identified for the different PM types measured

during a specific campaign did not necessarily all correspond to one and the same *case*, meaning that maximum concentrations were not always measured in the same location across the seasons. As such, in winter 2013 and winter 2014, highest maximum hourly indoor concentrations were measured in different houses (houses two (2) and 14 and in houses 19 and 14, respectively, for example).

Hourly maximum indoor and personal PM_4 concentrations measured across the campaigns are more often than not measured in the mg/m^3 range. This is not the case for most ambient PM_{10} and $PM_{2.5}$ concentrations. Some ambient $PM_{2.5}$ measurements taken at KZ-E4-SE in KwaZamokuhle show concentrations also reaching up into the mg/m^3 ranges (For *case* 4 in spring 2015, for *cases* 12,4,5,6 and 9 in summer 2016 and *cases* 1,2,4,6,8 and 9 in winter 2016). This might mean that there is a burning source located next to the E-Bam monitor, contributing to direct local suspended particle concentrations.

Most notably, it was observed from this exercise that, in some houses in KwaDela (house 3 in winter 2013 and summer 2015, house 15 in winter 2014 and summer 2014 as well as house 18 in summer 2014, winter 2014 and summer 2015) and in some houses in KwaZamokuhle (house 2 in summer 2016 and winter 2016, house 5 in spring 2015, summer 2016 and winter 2016 as well as house 6 in summer 2016 and winter 2016 and house 7 in winter 2016), though little to no coal burning activities were taking place internally, indoor PM concentrations showed similarly high concentrations as those houses in which burning did take place.

Additionally, it was noted that these houses showed higher concentrations than those concentrations measured in the ambient environment. This is most likely a sign that air pollution from a near-by, independent ambient source has filtrated into the indoor environment by entering through either open doors or windows or through cracks and fissures in the housing structure itself, raising air pollution levels in the household (Meng *et al.*, 2005; Hoek *et al.*, 2008). The magnitude of the high concentration events indicates that it is likely that these households must have been located in close proximity to other independent PM sources, speculatively, such sources could be external waste burning events, nearby social fires, veld fires or in the mornings, traffic related pollution. This means that, regardless of the source of energy that is utilised inside a household, the likelihood of the air quality in the indoor environment exceeding the NAAQS is high, and this in the summer as well as the winter months.

Interestingly, cases even exist where maximum values are higher in the ambient environment than in the indoor environment (*case* 13 in KwaDela in winter 2013 for example). This points to the fact that it is possible to have indoor PM concentrations that are lower than those that govern the ambient environment.

The results highlighted in this section are in line with previous studies that have examined extreme peak exposure events in the indoor environment in households which rely heavily on solid fuels. Rajagopalan and Brook (2012) reported peak exposures of > 30 000 µg/m^3 during periods of cooking. Hourly maximum concentrations measured in House 8 in KwaZamokuhle in winter 2016 went up to 32 000 µg/m^3 (Figure 7.7). Significantly, findings of this research also support findings made in other studies, where contributions of outdoor sources to indoor PM concentrations can be very high (Meng *et al.,* 2005).

Another important finding that is made here is that maximum PM concentration of all size fractions measured (PM_{10}, $PM_{2.5}$ and PM_4) are highly variable in space and time in both KwaDela and KwaZamokuhle. Though variability is visible for ambient maximum PM concentrations, it is more evident for personal measurements and particularly so for indoor measurements. Whilst considering each case on an individual basis, it is clear that indoor and personal maxima are on average higher than ambient maxima, the difference between the average maximum concentrations measured across the houses varies significantly, with some houses showing maximum hourly values within the range of ambient maximum concentrations, and others showing maximum concentrations that reach over 10 000 µg/m^3 in the winter season. This bears testimony to the fact that there is stark intra-urban contrast between measured maximum PM concentrations at an ambient, indoor and personal PM nature.

A detailed study conducted by a PhD student at the University of Canterbury sought to challenge the widely-held assumption that PM concentrations within an urban setting are spatially uniform, particularly so in a city which is affected by high seasonal variations of PM concentrations (Wilson, 2006). Wilson (2006), along with many other researchers, states that most epidemiological studies that statistically associate PM air pollution exposures with health outcomes make this assumption, and by inference, assume that, within a given city, exposures to PM concentrations are also without significant variability, which allows for the use of compliance status with ambient standards as a proxy for overall community health status (Oglesby *et al.,* 2000; Jantunen, 2007; Diapouli *et al.,* 2011). It is further stated that it is of critical importance to any environmental epidemiological work to determine an accurate exposure estimate

for a considered population or indeed, a considered individual (Chow *et al.*, 2006). It is suggested that there may be greater variation within urban areas than previously reported (Briggs *et al.*, 1997).

What this chapter emphasises is that, were this study based solely on PM measurements taken at a central ambient monitoring in both KwaDela and KwaZamokuhle, the true magnitude and the true variability of PM concentrations that is present in these communities in the various micro-environments would not come to the fore. It further emphasises that, even though KwaDela and KwaZamokuhle both represent low-income communities which lie in relative close geographical proximity to each other, and though they are governed by similar socio-economic demographics and similar macro-scale meteorological patterns, it is not possible to assume that these communities would have the same air quality, though air quality in both areas can be considered extremely poor.

A necessary and bold assumption of using a single monitoring site as a proxy for community-wide exposure, is that $PM_{2.5}$ concentrations are homogeneously distributed and that the concentrations between sites are well correlated in space, magnitude and time (Pinto *et al.*, 2004; Wilson, 2006). The next section of this thesis aims to better understand correlations between PM measurements recorded at different locations in both KwaDela and KwaZamokuhle.

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This chapter outlined results and discussions unpacking the first objective of the study which sought to "characterise ambient, indoor and personal PM concentrations in KwaDela and KwaZamokuhle". This chapter also attempted to address, in part, the second objective of this study "Determine the relationships between ambient, indoor and personal PM concentrations on KwaDela and KwaZamokuhle, Mpumalanga". The next chapter aims to unpack objective two in more detail. Additionally, chapter 5 addresses objective three: "Assess personal total exposure to PM in KwaDela".

Chapter 5 Relationships between and personal exposure to particulate matter concentrations

This chapter presents results from two households selected in both KwaDela and KwaZamokuhle to explore the relationship between ambient, indoor and personal PM concentrations in individual households and the possible determining factors of these relationships. Additionally, results of *case*-level and community-level regression analyses are presented and discussed. Finally, a case study of a single household is discussed to assess personal exposure to PM concentrations.

5.1 Household-level PM characteristics

Though socio-economic factors have been taken into account in interpreting the overarching PM concentration variability at a community level in the sections above, it is useful to consider individual households to better understand how people's day-to-day habits can influence PM concentrations measured directly in and around the house and how these relate to total personal exposure levels.

Two houses for each of the sampling campaigns have been selected to illustrate the contribution of household-level factors to PM concentrations. Houses 3 and 11 in KwaDela and houses 3 and 9 in KwaZamokuhle were selected, as these were the houses for which *case*-level data (i.e. measurements for each of the PM types (ambient, indoor and personal PM)) were available simultaneously for three campaigns. This allowed for a good comparison of data across the seasons. Survey data, as collected during these respective campaigns has been used to better understand contributing factors to air pollution levels in and around these households (Table 5.**1** and Table 5.2).

Table 5.1. Overview of relevant survey results for chosen households in KwaDela

	House 3KD	House 11KD
House type	Formal (brick)	Formal (brick and corrugated iron, but not extended)
Stove type	No coal stove	Welded (Union)
Energy sources used	Electricity	Electricity, coal, wood and dung
Lighting	Electricity	Electricity
Use of coal for heating	No	Yes
Use of coal for cooking	No	Yes
Other uses for coal	NA	Heating water for bathing and washing dishes in winter, ironing
Ignition times in winter	NA	5pm – 9 pm
Ignition times in summer	NA	5pm
Purchase coal	NA	As needed
Smoker	No	Yes. One individual smokes, but it is not known whether he/she smokes indoors

Table 5.2. Overview of relevant survey results for chosen households in KwaZamokuhle

	House 3KZ	House 9KZ
House type	Formal (brick) with informal house extension	Formal (brick)
Stove type	Cast iron stove	Welded stove
Energy sources used	Coal and electricity	Coal and electricity
Lighting	Electricity	Electricity
Use of coal for heating	In winter only	In winter only
Use of coal for cooking	In winter and summer	In winter and summer
Other uses for coal	Bathing in winter, washing dishes in winter	Bathing in summer and winter and socialising
Ignition times in winter	6 am and 4 pm	6 am and 4 pm
Ignition times in summer	7 am	5 am
Purchase coal	As needed @ small bag of 25kg	Monthly @ small bag of 25kg
Smoker	Yes. Two individuals smoke, but it is not known whether they smoke indoors	No

5.1.1 Characterising PM concentrations at a household level

Daily average PM concentrations of all PM type measurements in KwaDela for *cases* 3KD and 11KD were on average higher in winter than in summer (Figure 5.1). Though indoor PM_4 daily average concentrations were higher in the winter time than in the summer time, the 75^{th} percentile value of the indoor PM_4 daily average values was higher in the summer months than in the winter months and maximum daily average concentrations measured in summer were comparable to those measured in winter. Overall, indoor PM_4 concentrations measured for *case* 11KD were higher than those measured for *case* 3KD. This applies to all seasons. Median personal daily average values did not correspond with median indoor daily average values at a *case* level. Ambient daily average values measured were similar when comparing both *cases* for each individual season, and highest, overall, in winter.

Lowest daily average concentrations were observed for both *cases* in KwaZamokuhle in summer (Figure 5.2). Highest ambient median concentrations were evident for $PM_{2.5}$ measurements taken at the KZ-E4-SE monitoring site and the PM_{10} measurements taken at the main AMS in summer. In spring, daily average indoor and personal PM_4 concentrations were on average, higher than those measured in summer, however, highest median concentrations were measured for both *cases* in winter. Indoor and personal median daily average concentrations corresponded well across the sampling campaigns, but most obviously so in winter. Winter concentrations were more variable than spring concentrations and spring concentrations were more variable than summer concentrations.

Figure 5.1. Comparing ambient, indoor and personal daily average PM concentrations (µg/m³) measured per season for *case* 3KD and *case* 11KD in KwaDela

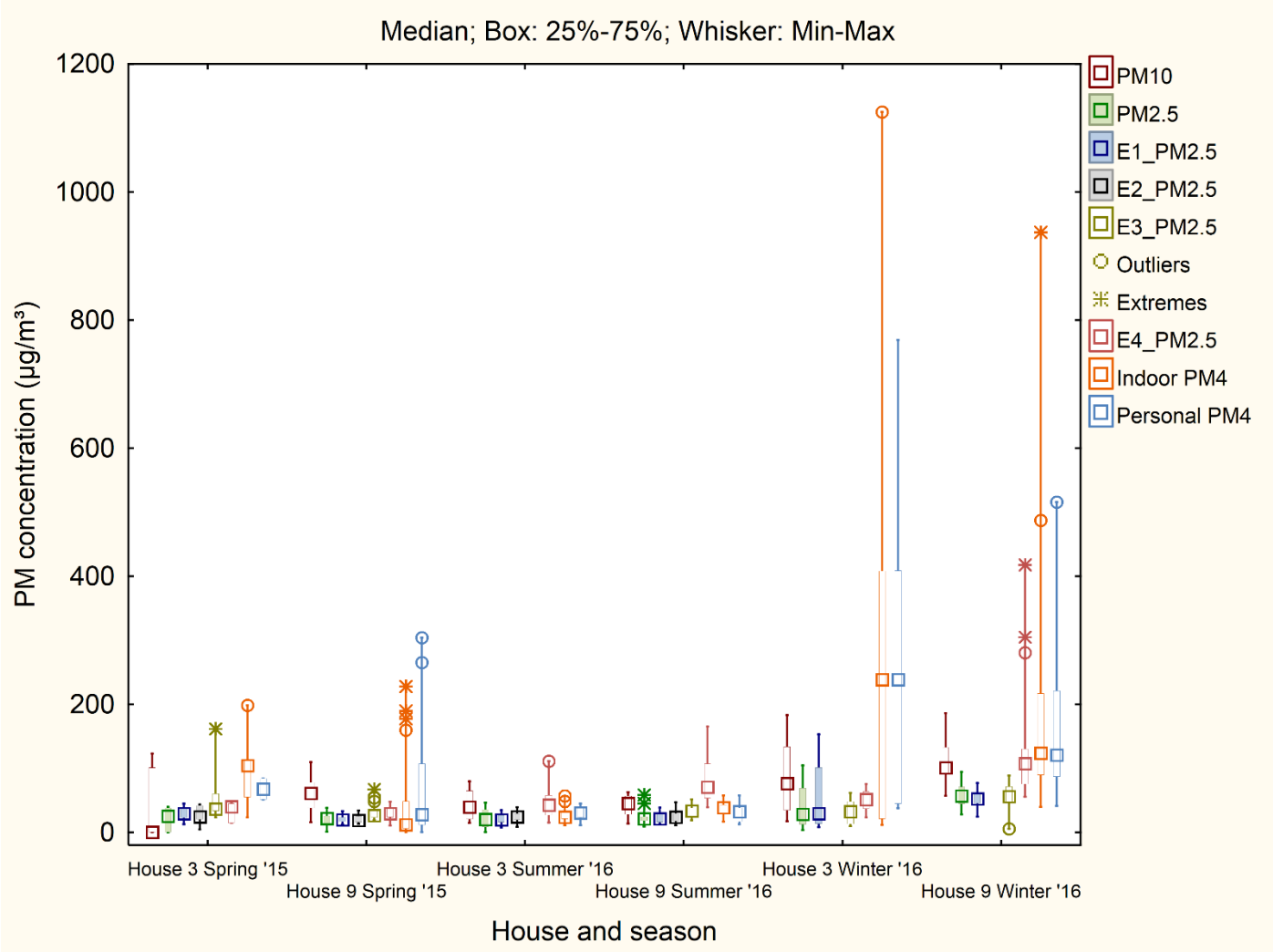


Figure 5.2. Comparing ambient, indoor and personal daily average PM concentrations (µg/m³) measured per season for *case* 3KZ and *case* 9KZ in KwaZamokuhle

In KwaDela, collected survey data indicated that House 3KD does not use coal as its main energy source, not even for cooking and heating activities (Table 5.**1**). In stark contrast, house 11KD relies on a range of sources to cover its energy needs (electricity is used for lighting, wood, coal and dung are used for heating, cooking, ironing, heating water for bathing and washing dishes). This background information can help contextualise the measured data, and thus it makes sense that indoor and personal PM measurements taken in house 11KD would be higher than those measured in house 3KD, as more indoor air pollution is being created through the solid fuel combustion processes in the indoor environment. The fact that house 11KD also makes mention of corrugated iron as a structural element of the house, could also mean that infiltration of ambient air into the indoor environment could play a large role in defining indoor air quality due to

unsealed sections of the house structure. Significantly, though house 3KD does not make use of dirty fuels inside the house itself, high PM concentrations are nonetheless measured in the inside environment during peak burning times, so much so, that indoor measurements in house 3KD are sometimes measured to be higher than those measured in house 11KD. High indoor PM concentrations in house 3KD could be attributed to smoke, from a neighbouring house or a fire close by, infiltrating directly into the house. An unaccounted for indoor source, such as an individual's smoking habits could also contribute to higher PM concentrations indoors. When considering the social survey data however, it is noted that there is no smoker in house 3KD, supporting the case that infiltration of ambient PM into the indoor environment is more than likely the main contributory cause for high PM emissions in house 3KD. The fact that there is a smoker in house 11KD is another reason for high indoor PM concentrations.

Survey data for the two houses showcased for KwaZamokuhle (Table 5.2), implies that the indoor PM monitor in house 9KZ would read, on average, higher PM concentrations than the monitor in house 3KZ. This assumption is based on the fact that the household member in house 9KZ expressed a preference for using coal over electricity for heating and cooking purposes, and additionally, the household burns coal to heat water for bathing purposes in winter months and summer months as well as for social gatherings (whereas this is not the case in house 3KZ). Additionally, the coal stove used in house 9KZ is welded, as opposed to the cast iron stove used in house 3KZ. A welded stove could presumably be more prone to leaks and therefore would possibly allow more smoke to escape from the burning chamber directly into the household, instead of from the chimney into the ambient environment, as would be the case for a cast iron stove.

The fact that measured PM concentrations in house 3KZ however, are in fact higher than those measured in house 9KZ, is a perfect illustration of how complex it is to understand indoor air pollution. There are many other factors that could influence the indoor PM concentrations in these households, over and above those listed in the table above. These could explain the, on average, higher concentrations in house 3KZ; open doors or windows in house 9KZ during peak burning times could lead to lower indoor PM concentrations, for instance, through dispersion of pollutants into the ambient environment. It should be factored into this interpretation that house 3KZ has an informal extension. It is possible that the extension is where burning activities take place. Smoke from these burning activities could easily infiltrate into the main brick building, through cracks or open windows/ doors increasing indoor PM concentrations there.

Considering the ambient PM daily average concentrations measured during the same time, it seems unlikely that general ambient PM concentrations would have caused a large contribution to higher indoor PM concentrations in house 3KZ in the winter time. Higher summer indoor PM concentrations in house 9KZ could be attributed to the burning of coal in summer months for bathing and cooking purposes. When social survey data is brought into the picture, it becomes clear, as in the KwaDela case study, that smoking in the indoor environment could contribute greatly to indoor air pollution: The social survey data from house 3KZ indicated that an individual living in the household was an active smoker. Whether or not this person smoked inside the house is not known, but it cannot be denied that this could be the reason the indoor PM measurements were high in this home. There was no smoker in house 9KZ.

A very clear observation is that the indoor and personal daily average readings measured for both households in KwaZamokuhle correspond highly in winter, most likely indicating that the person wearing the PM monitor spent more time inside the house in question during colder months, possibly even igniting the fire, supporting that the individual was more exposed to the indoor air pollution.

5.1.2 Temporal variation of particulate matter concentrations at a household level

Diurnal hourly average trends, as ascertained at the community level in chapter 4 are reiterated here as measured for the four (4) *cases*. On average, morning peak concentrations were measured between 5 - 10 am and evening peaks were measured between 5 – 9 pm in the four (4) households considered in this section of the study (Figure 5.3 - Figure 5.8). For every *case*, indoor and personal PM_4 concentrations were not only consistently the highest measured concentrations when compared to ambient concentrations, but also the most variable. PM concentrations of all types were consistently found to be highest in winter and higher in spring than in summer. Personal PM_4 measurements were typically only available for the day hours in KwaDela, but for day and night time hours in KwaZamokuhle. This represents one of the limitations of the study, as conclusions are being drawn on an incomplete personal PM_4 data set in KwaDela.

Other overarching recognisable trends are burning times which correspond inversely with ambient temperatures, where lowest ambient temperatures typically represent times of peak burning activity and

highest PM concentrations in the indoor and the ambient environment. Indoor PM peak concentrations do not always correspond directly with ambient PM peak concentrations, regardless of the size fraction measured (PM_{10} or $PM_{2.5}$), though a general trend towards early morning and late afternoon elevated average concentrations is measured for both ambient and indoor PM. Non-corresponding peaks could be attributed to lag effects, where it takes a while for ambient air to infiltrate into the indoor environment or vice versa. This could very likely be the case in house 3KD in KwaDela in particular, where indoor PM concentrations are high, though no coal burning activities take place. This remains mere speculation though, and this would have to be confirmed with infiltration rate measurements. Additionally, times in which indoor and personal PM concentrations do not follow the same diurnal trend as ambient concentrations, could point to different aerosol source contributions (House 11KD in winter 2014 in KwaDela and house 3KZ in summer 2015 in KwaZamokuhle). Where ambient concentrations are likely to be influenced by all domestic burning activities taking place in the community during the course of the day and traffic during the early hours of the morning and the later hours of the afternoon, indoor concentrations are, to a large degree, likely to be determined by indoor sources stemming from the particular house in question, and to a smaller degree by ambient sources.

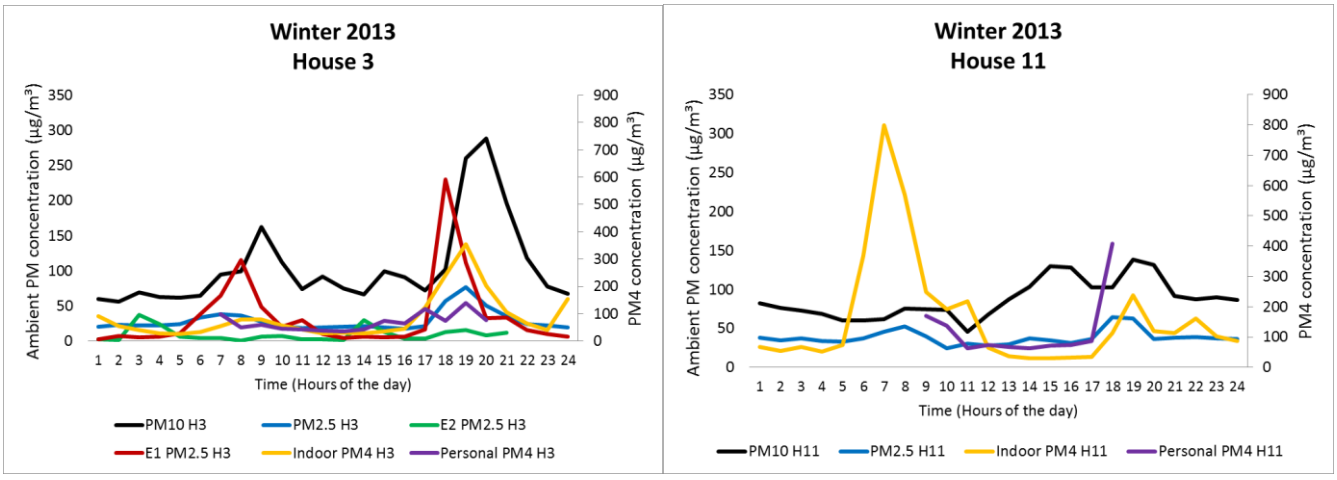
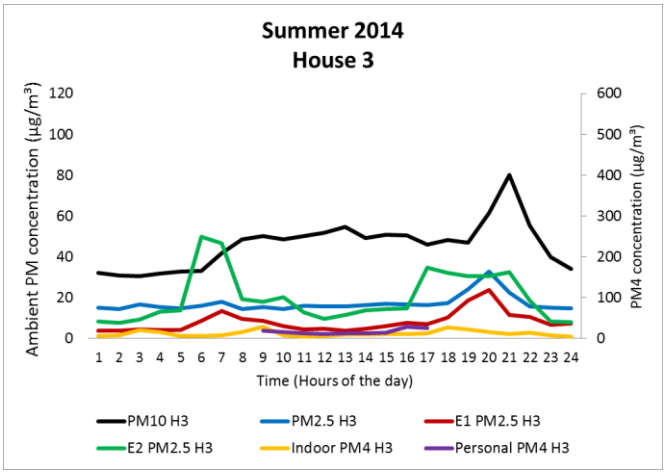


Figure 5.3 Diurnal variation of particulate matter (µg/m³) for houses 3KD and 11KD in KwaDela in Winter 2013



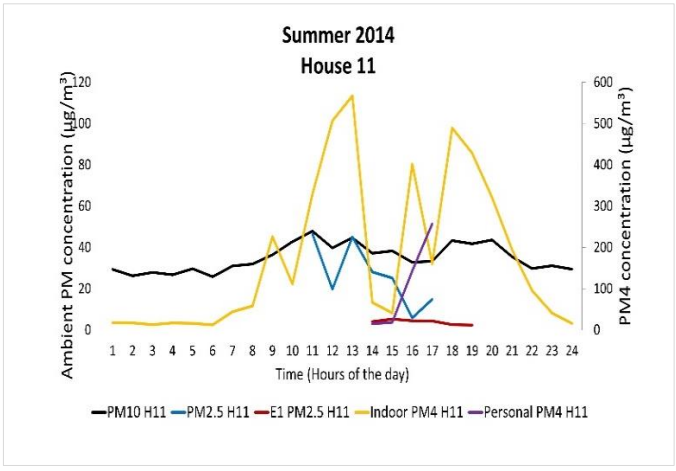
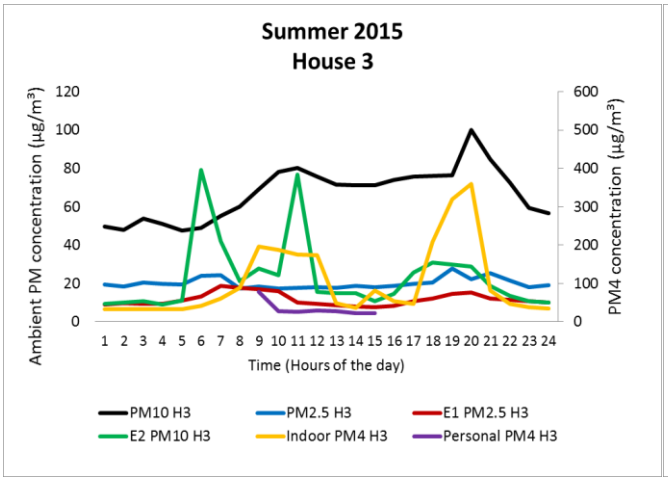


Figure 5.4 Diurnal variation of particulate matter (µg/m³) for houses 3KD and 11KD in KwaDela in Summer 2014



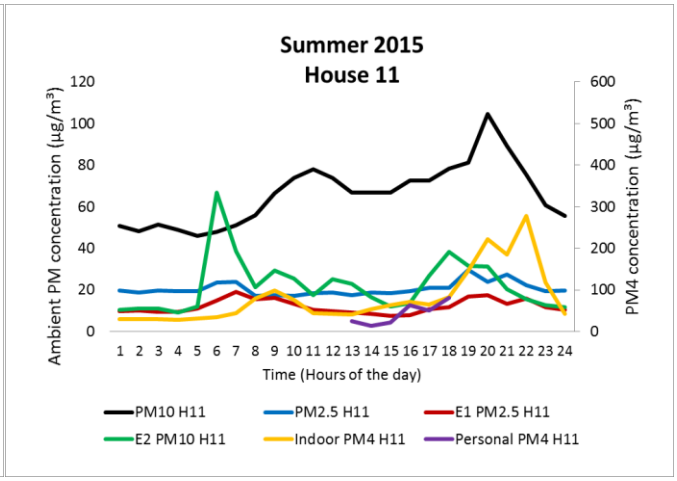


Figure 5.5 Diurnal variation of particulate matter (µg/m³) for houses 3KD and 11KD in KwaDela in Summer 2015

Hourly averge PM concentrations measured for the selected *cases* in KwaDela are well explained by considering survey data collected. Diurnal bimodal peaks re-emphasise seasonal trends illustrated by daily average measurements where higher emissions are measured in winter than in summer. At a first glance, it is immediately apparent that hourly indoor and personal PM_4 concentrations measured in house 11KD are higher than those measured in house 3KD (except in summer 2015). Erratic hourly indoor measurements measured in house 11KD in summer 2014 could be attibutable to numerous burning times during the day adopted for cooking in the morning, midday and then again in the evening (Figure 5.3 - Figure 5.5). Again it is evident that indoor concentrations in house 3KD are high during peak burning times, even though no burning takes place in that specific house, according to survey data.

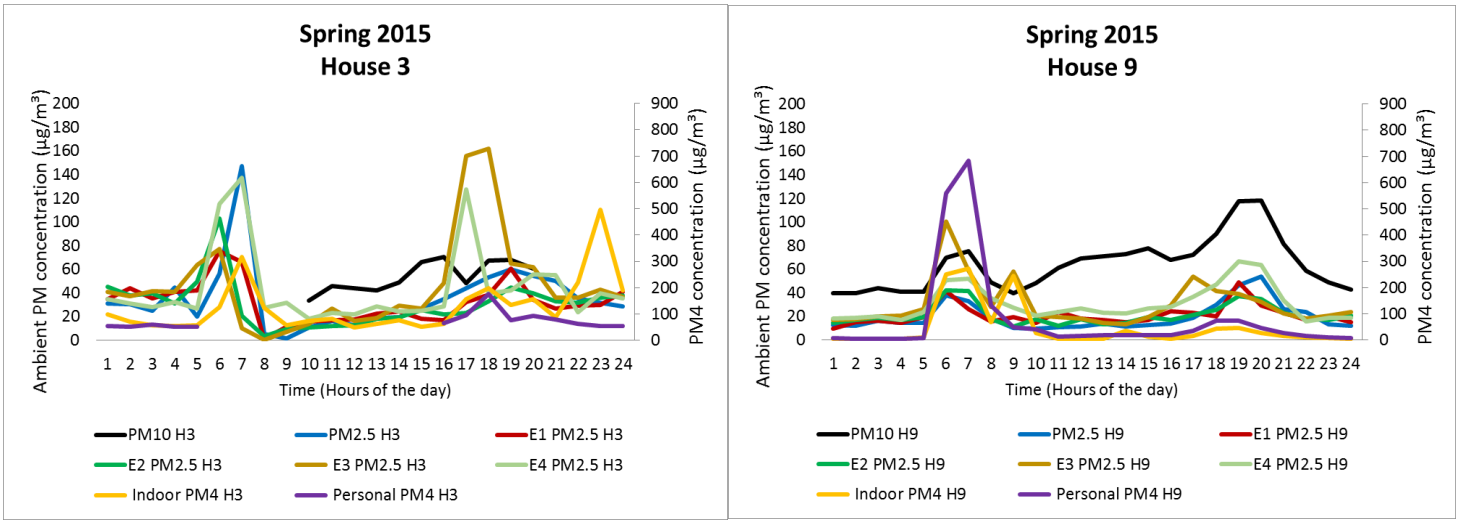


Figure 5.6 Diurnal variation for houses 3KZ and 9KZ in KwaZamokuhle in Spring 2015

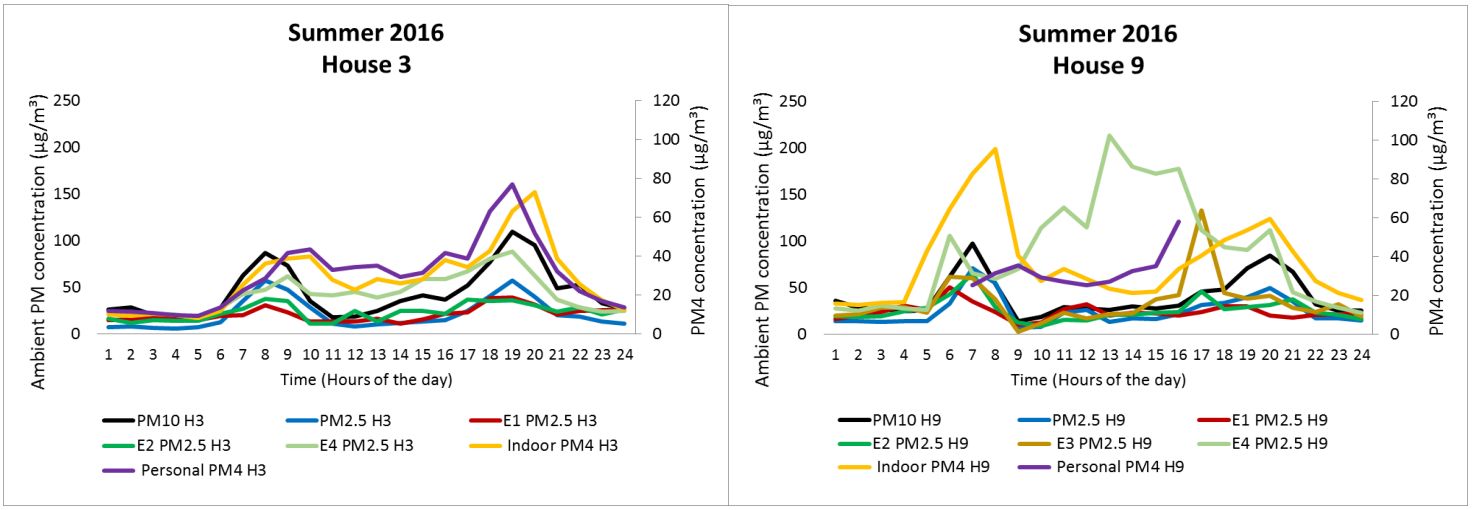


Figure 5.7 Diurnal variation for houses 3KZ and 9KZ in KwaZamokuhle in Summer 2016

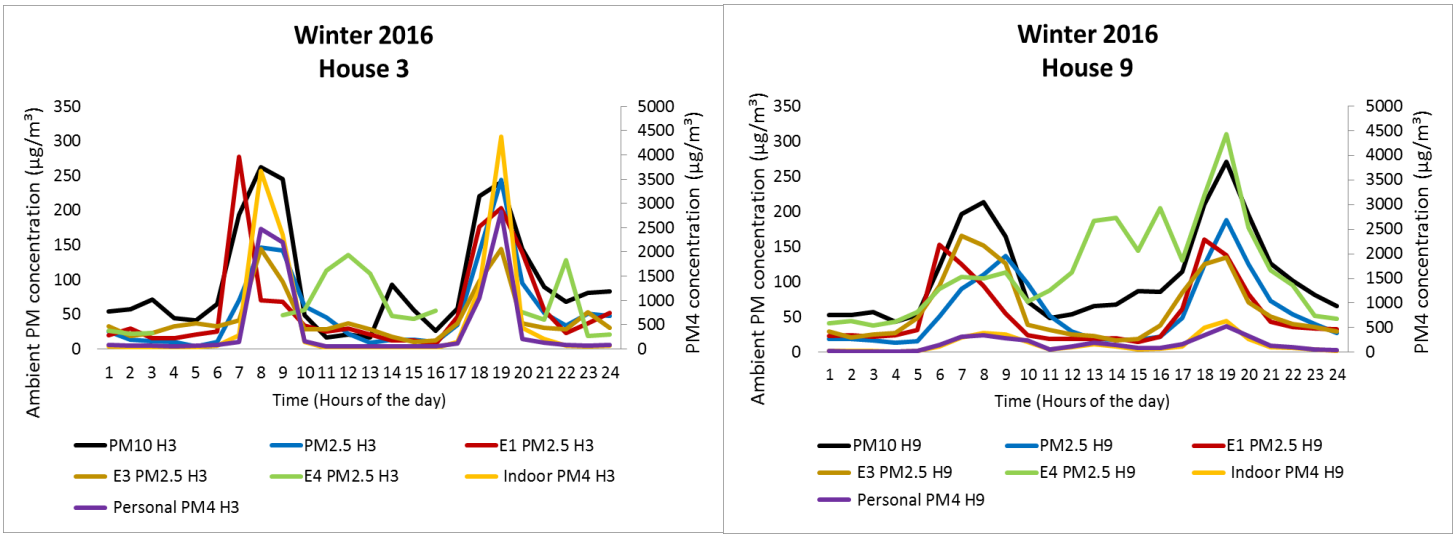


Figure 5.8 Diurnal variation of particulate matter (µg/m³) for houses 3KZ and 9KZ in KwaZamokuhle in Winter 2016

Peaks of hourly average concentrations of all PM types were evidently bimodal in all seasons in KwaZamokuhle (Figure 5.6 - Figure 5.8). Uncharacteristically, intermittent daytime peaks were measured at the KZ-E4-SE monitoring site in summer 2016. Indoor peak concentrations correspond well with survey results received where burning times in the mornings in House 9KZ start earlier in winter months than burning times in house 3KZ. The late afternoon burning evidently starts from 4pm, as also indicated in the surveys. Higher hourly average indoor and personal concentrations were also measured in house 3KZ in winter, which talks to the higher daily average concentrations that were measured for the same house for the same season.

5.2 Relationships between ambient, indoor and personal PM concentrations

Trends of closely matching indoor and personal PM concentrations, as suggested in the sections above, point to the fact that total exposure to PM (as measured by the SidePaks) can be heavily defined by PM concentrations stemming from the indoor micro-environment within which an individual is situated (Long & Sarnat, 2004).

PM concentrations stemming from sources in the ambient environment can influence concentrations measured indoors, if infiltration occurs. Conversely, indoor air pollution can escape from chimneys or diffuse through gaps in a household structure to influence the ambient air (Meng *et al.*, 2005). Bearing

this in mind, it could be expected that, were one to juxtapose different PM measurements taken at the same time, but in different locations through means of regression analysis, that distinct relationship trends could be defined (Wilson *et al.*, 2000).

5.2.1 PM concentration relationships at a community level

When comparing PM types in KwaDela and KwaZamokuhle at a community level, no real clear discernible relationship trends could be found between PM concentrations measured at different monitoring sites (Figure 7.8 - Figure 7.15 in Annexure B). Low coefficients of determination were found for most regression analyses conducted at a community-level between indoor and ambient, as well as personal and ambient concentrations for all ambient PM types considered. Plotting different ambient PM concentrations from different E-Samplers/E-Bams against each other rendered similarly low coefficients of determination. This pertains to both KwaDela and KwaZamokuhle. On average, highest R^2 values were found when plotting indoor and personal PM_4 concentrations against each other. Two household-level case studies have been extracted in Section 5.2.2 of this chapter to better showcase these *case*-level relationships between hourly average ambient, indoor and personal concentrations (Table 5.5 and Table 5.6).

At a community-level, it was difficult to ascertain whether there were any meaningful overarching relationship trends that governed whether or not the variation in one PM type could explain the variation in another PM type. This is true for all seasonal campaigns when plotting ambient, indoor and personal PM parameters against each other at every possible combination. Single ad hoc high R^2 values were found, but it is difficult to unpack these cases, as explanations are more based on speculation, rather than facts (Figure 7.8 - Figure 7.15 in Appendix B):

In KwaDela, in winter 2013 for instance, of the 14 regressions that were plotted for hourly maximum concentrations, eight (8) of the regressions showed high R^2 values ($R^2 > 0.6$). In winter 2014 however, only three (3) of the same 14 regressions that were plotted for hourly maximum concentrations showed high R^2 values. Across all sampling campaigns, only three (3) instances existed in KwaDela and four (4) instances existed in KwaZamokuhle, where the regressions for daily- and hourly mean as well as daily- and hourly maximum concentration regressions all showed high R^2 values consistently across the

campaigns. This leads to the assumption that there could well be a meaningful overarching relationship observable. These instances have been singled out for interpretation (Table 5.3 and Table 5.4).

Table 5.3. Overview of singled out highest coefficients of determination (R^2) resulting from community level regression analyses in KwaDela

	Campaign	Regression	Daily average	Daily maximum	Hourly average	Hourly maximum
1)	Winter 2013	PM_{10} **vs** $PM_{2.5}$	0.8770	0.9416	0.9221	0.8292
2)	Winter 2013	$PM_{2.5}$ **vs** PPM_4	0.7063	0.9111	0.8640	0.8606
3)	Summer 2014	$PM_{2.5}$ **vs** IPM_4	0.6000	0.7963	0.7531	0.7546

Table 5.4. Overview of singled out highest coefficients of determination (R^2) resulting from community level regression analyses in KwaZamokuhle

	Campaign	Regression	Daily average	Daily maximum	Hourly average	Hourly maximum
1)	Spring 2015	KZ-E1-N **vs** KZ-E2-NW	0.7803	0.7864	0.9424	0.8959
2)	Spring 2015	KZ-E2-NW **vs** KZ-E3-W	0.6750	0.8996	0.7622	0.8242
3)	Spring 2015	IPM_4 **vs** PPM_4	0.7320	0.5400	0.7571	0.9575
4)	Summer 2016	PM_{10} **vs** PPM_4	0.9327	0.7623	0.7941	0.8364

A higher coefficient of determination, as listed in the tables above, would indicate that the concentrations of the various PM types that have been plotted against each other in the regression analysis, have common sources or are affected by the same processes, as they follow the same trends, whereas a lower coefficient of determination would indicate the source contribution of varying sources to the various PM size fractions (Alves *et al.,* 2014). This means that, for instance, in summer 2016 in KwaZamokuhle (Ambient PM_{10} vs Personal PM_4 daily average concentrations, R^2 = 0.9327), 93% of the variation in personal PM_4 concentrations could be explained by the variation in ambient PM_{10} concentrations. In an attempt to interpret this strong correlation, one could say that, as these figures represent community-wide trends, the majority of people wearing personal monitors during summer 2016 spent a large proportion of their time in the ambient environment and were thus subjected to the same or similar sources or processes that influenced the concentrations measured at the AMS during that period. Of course, this is a hypothetical and simplified interpretation based on assumptions, and the cause for the high correlation could only truly be understood taking into account a range of complexities, such as cumulative time-activity patterns of individuals as well as larger- and smaller scale factors that influenced the ambient particulate concentrations measured during that time.

5.2.2 PM concentration relationships at a household level

When considering relationships between PM types at a case level, no consistent relationship trends could be found i.e. at a household level between the various PM measurements. As such, there was no combination of PM types that rendered consistently high coefficients of determination across the board. High R^2 values are highlighted in red.

Out of all PM type regression combinations, the variability in indoor hourly average concentrations was, however, most likely to explain the variability in the personal hourly average concentrations. For purposes of demonstration, cases 3KD and 11KD in KwaDela and 3KZ and 9KZ in KwaZamokuhle were considered (Table 5.5 and Table 5.6). Three (3) out of six (6) R^2 values in KwaDela and four (4) out of six (6) R^2 values in KwaZamokuhle resulting from plotting indoor against personal PM concentrations showed R^2 values >0.5. The high correspondence between indoor and personal PM values measured has been repeatedly noted in results discussed in section 4.1.5 in Chapter 4 and in results discussed in this chapter.

In cases in which high R^2 values were found for PM type combinations other than indoor and personal PM concentrations, it becomes difficult to understand, with certainty, what could have contributed to the good correlation. For example, in KwaDela, three (3) out of six (6) correlation coefficients of determination showed high R^2 values when plotting hourly average $PM_{2.5}$ concentrations measured at KD-E1-NW against indoor PM_4 concentrations, two of which were noted for winter 2013 when using indoor measurements from house 3KD and house 11KD. The location of KD-E1-NW in respect to house 3KD and house 11KD is very different, indicating that whatever source contributions defined ambient $PM_{2.5}$ concentrations at that location could have simultaneously defined indoor PM concentrations in houses 3KD and 11KD. PM concentrations are generally high in winter, regardless of the micro-environment or PM type considered. Hence, it is more likely that overarching increases in burning practices taking place in different places in winter at specific times of the day caused PM concentrations in the ambient and indoor environment to rise or fall concurrently.

In KwaZamokuhle, coefficients of determination were generally below 0.5 indicating that the variability of one PM type was less likely to explain the variation of another PM type most of the time.

Table 5.5. Correlation coefficients of determination for hourly average PM types per house, per season in KwaDela

	Winter 2013		Summer 2014		Summer 2015	
	House 3	**House 11**	**House 3**	**House 11**	**House 3**	**House 11**
PM10 vs PM2.5	0.2797(*)	0.2797(*)	0.1877(*)	0.0680	0.2119(*)	0.2496(*)
PM10 vs E1PM2.5	0.3283(*)	0.3283(*)	0.2206(*)	0.8547(*)	0.3084(*)	0.3030(*)
PM10 vs E2PM2.5	0.0336	0.0336	0.0044	-	0.3909(*)	0.3061(*)
PM10 vs IPM4	0.3814(*)	0.3814(*)	0.0617(*)	0.0293	0.3434(*)	0.2582(*)
PM10 vs PPM4	0.2863	0.2863	0.4455(**)	0.9851(*)	0.7967(*)	0.2348
PM2.5 vs E1PM2.5	0.6464(*)	0.6463(*)	0.2589(*)	-	0.3075(*)	0.3362(*)
PM2.5 vs E2PM2.5	0.0345	0.0345	0.0086	-	0.2866(*)	0.2907(*)
PM2.5 vs IPM4	0.4326(*)	0.4326(*)	0.0546(*)	0.0007	0.1494(*)	0.1486(*)
PM2.5 vs PPM4	0.3574	0.1147(**)	0.1965	0.9888(*)	0.0180	0.6399(*)
E1PM2.5 vs E2PM2.5	-	-	0.0010	-	0.4260(*)	0.4221(*)
E1PM2.5 vs IPM4	0.5250(*)	0.5257(*)	0.1715(*)	0.7580(**)	0.2824**)	0.2188(*)
E1PM2.5 vs PPM4	-	-	0.7216(*)	-	0.4703	0.3961(**)
E2PM2.5 vs IPM4	0.0208	0.0208	0.0008	-	0.3464(*)	0.2318(*)
E2PM2.5 vs PPM4	-	-	0.4287	-	0.0656	0.5126(*)
IPM4 vs PPM4	0.6207(*)	0.1589(**)	-	0.8921	0.0811	0.9714(*)

*correlation is significant at the 0.01 level
**correlation is significant at the 0.05 level

It can be assumed that the R^2 values could improve between indoor and ambient concentrations if a lag effect were factored into the metaphorical equation. Studies have shown that there is a well-known lag between indoor and outdoor concentrations caused by the penetration time needed for ambient concentrations to come in through the building envelope (Guo *et al.*, 2010). The duration of this lag effect depends on many factors. If windows and doors are open for example, ambient air pollution can quickly infiltrate the indoor environment. Air entering the indoor environment through smaller cracks in the walls of the roof of the house, on the other hand, would infiltrate at a slower rate (Guo *et al.*, 2010).

Table 5.6. Correlation coefficients of determination for hourly average PM types per house, per season (KwaZamokuhle)

	Spring 2015		Summer 2016		Winter 2016	
	House 3	House 9	House 3	House 9	House 3	House 9
PM10 vs PM2.5	0.5388(*)	0.4290(*)	0.6394(*)	0.3932(*)	0.3560(*)	0.3003(*)
PM10 vs E1PM2.5	0.0685	0.1565(*)	0.2714(*)	0.1364(*)	0.4441(*)	0.2444(*)
PM10 vs E2PM2.5	0.0376	0.1243(*)	0.3502(*)	0.2231(*)	-	-
PM10 vs E3PM2.5	0.0075	0.1153(*)	-	0.2448(*)	0.2373(*)	0.2699(*)
PM10 vs E4PM2.5	-	0.2071(*)	0.2796(*)	0.0000	0.0031	0.2637(*)
PM10 vs IPM4	0.2731(**)	0.0130(**)	0.4175(*)	0.1625(*)	0.4971(*)	0.2102(*)
PM10 vs PPM4	-	0.0103	0.2532(*)	0.0007	0.3547(*)	0.2061(*)
PM2.5 vs E1PM2.5	0.4277(*)	0.2311(*)	0.2621(*)	0.1777(*)	0.3191(*)	0.2240(*)
PM2.5 vs E2PM2.5	0.3359(*)	0.1947(*)	0.3717(*)	0.2572(*)	-	-
PM2.5 vs E3PM2.5	0.2496(*)	0.2098(*)	-	0.2943(*)	0.1879(*)	0.2751(*)

PM2.5 vs E4PM2.5	0.3092(*)	0.2536(*)	0.2040(*)	0.0027	0.1467	0.2038(*)
PM2.5 vs IPM4	0.3022(*)	0.0261(*)	0.4640(*)	0.2115(*)	0.2847(*)	0.2021(*)
PM2.5 vs PPM4	-	0.0426(*)	0.3292(*)	0.0251	0.2940(*)	0.2380(*)
E1PM2.5 vs E2PM2.5	0.4549(*)	0.1708(*)	0.3975(*)	0.3353(*)	-	-
E1PM2.5 vs E3PM2.5	0.1430(*)	0.1467(*)	-	0.2638(*)	0.2314(*)	0.4177(*)
E1PM2.5 vs E4PM2.5	0.1953(*)	0.2449(*)	0.1958(*)	0.0025	0.1389	0.1124(*)
E1PM2.5 vs IPM4	0.1067(*)	0.0264(*)	0.2082(*)	0.1337(*)	0.5761(*)	0.2751(*)
E1PM2.5 vs PPM4	0.0579	0.0502(*)	0.0941(*)	0.1888(*)	0.4441(*)	0.2588(*)
E2PM2.5 vs E3PM2.5	0.3168(*)	0.1840(*)	-	0.4577(*)	-	-
E2PM2.5 vs E4PM2.5	0.2770(*)	0.1205(*)	0.1750(*)	0.0007	-	-
E2PM2.5 vs IPM4	0.0828(**)	0.1195(*)	0.2609(*)	0.3167	-	-
E2PM2.5 vs PPM4	0.0198	0.0652(*)	0.1172(*)	0.2790(*)	-	-
E3PM2.5 vs E4PM2.5	0.2265(*)	0.0758(*)	-	0.0018	0.0111	0.0556
E3PM2.5 vs IPM4	0.0880(**)	0.0880(*)	-	0.1599(*)	0.3969(*)	0.4670(*)
E3PM2.5 vs PPM4	0.0610	0.0569(*)	-	0.1340(*)	0.5044(*)	0.3938(*)
E4PM2.5 vs IPM4	0.2052(*)	0.0057	0.2385(*)	0.0141	0.0032	0.1134(*)
E4PM2.5 vs PPM4	-	0.0464(*)	0.1920(*)	0.0589(**)	0.0722	0.1388(*)
IPM4 vs PPM4	0.8959(*)	0.5351(*)	0.4905(*)	0.1086(*)	0.8796(*)	0.8434(*)

*correlation is significant at the 0.01 level
**correlation is significant at the 0.05 level

Considering the above outlined, it becomes clear once again that PM concentrations in the low-income context are highly variable in space and time and so it is very difficult to understand and ascertain meaningful relationships.

5.2.3 Ratios between indoor and personal PM measurements

Regression analyses are one way to determine relationships between varying PM types. Ratios represent another means to gain an understanding of whether or not a relationship exists between PM measurements (Chen & Zhao, 2011). The hourly average Personal PM_4/ Indoor PM_4 ratios for the case study houses differed in all houses and across the seasons (Figure 5.9). In KwaDela, the Personal PM_4/ Indoor PM_4 ratio for cases 3KD and 11KD were > 1 most of the time, except for case 11KD in winter 2013 during the late afternoon and case 3KD between 10:00 and 12:00 in the day. Notably, the highest ratios were evident during the middle of the day in all seasons and also in the early hours of the evening for case 3 in winter 2013. This could mean that the person wearing the SidePak monitor was outside, and not exposed to high indoor concentrations during the day, particularly so in summer and during the evenings in winter 2013. It is reiterated that personal measurements were not available for the earliest hours of the morning and the latest hours of the afternoon in KwaDela.

Personal PM_4/ Indoor PM_4 ratios in KwaZamokuhle were closer to one (1) across all seasons and across most hours of the day. The Personal PM_4/ Indoor PM_4 ratio was found to be >1 in the early hours of the morning for case 9KZ in spring and in summer and in particular, in the late hours of the night for case 3KZ in spring. The individual in case 3KZ seems to spend more time indoors than the individual in case 9KZ, as indoor and personal concentrations correspond.

The hourly average Personal PM_4/ Ambient $PM_{2.5}$ ratios were more often than not >1, indicating that indoor PM_4 concentrations were higher than ambient $PM_{2.5}$ concentrations most of the time (Figure 5.10). This was particularly the case in the early mornings and the evenings, as per the typical diurnal peaks illustrated in all hourly average timeseries graphs plotted for this study.

The non-congruence between ambient and indoor PM measurements is most likely to be attributed to the various source contributors: indoor PM concentrations will more than likely have been governed by localised indoor burning practices, whereas ambient concentrations will have been governed by a combination of various external source contributors. These findings echo what has been found in other research studies, namely that personal exposure to PM is on average, poorly correlated with ambient concentrations and more highly correlated with indoor concentrations (Janssen, 2005).

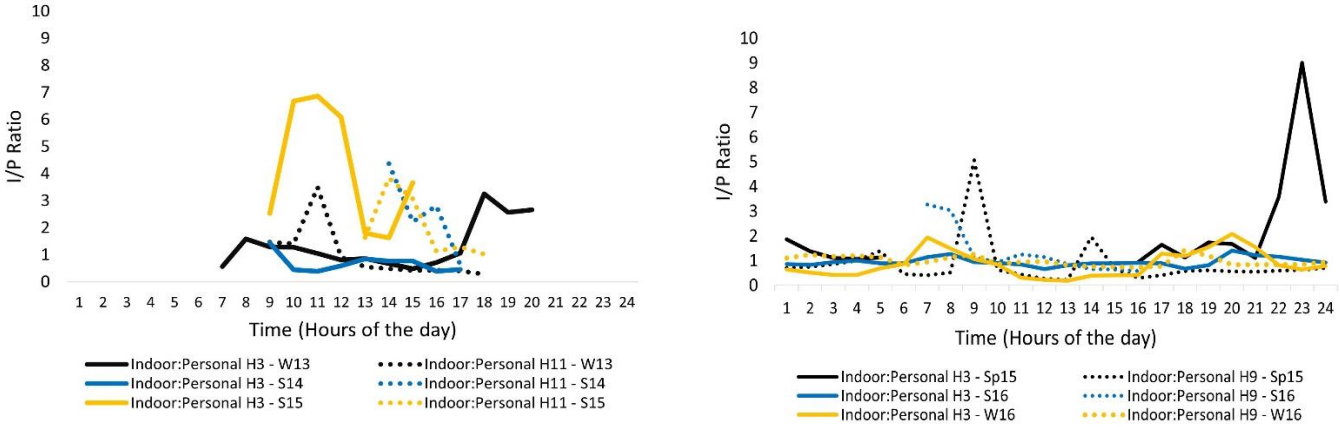


Figure 5.9. Hourly average Personal PM_4/ Indoor PM_4 ratio in KwaDela (left) and KwaZamokuhle (right)

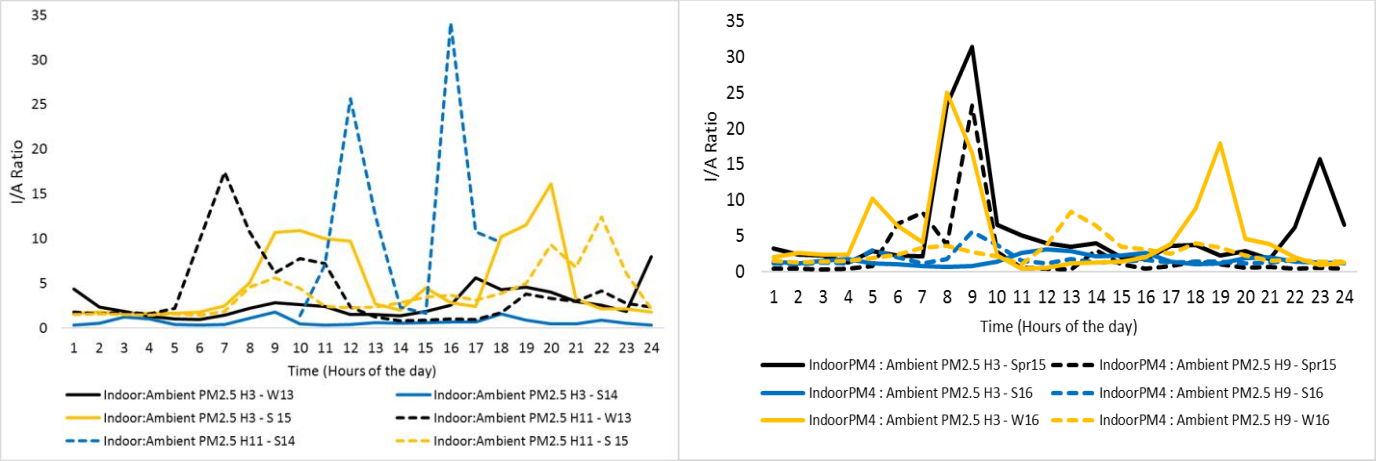


Figure 5.10. Hourly average Personal PM_4/ Ambient $PM_{2.5}$ ratio in KwaDela (left) and KwaZamokuhle (right)

5.3 Personal total exposure to particulate matter concentrations in various micro-environments

5.3.1 The identification of micro-environments in KwaDela

Total exposure takes into account the period of time an individual comes into contact with an exposure concentration throughout the day and in various micro-environments (U.S. EPA 1992). In KwaDela, total exposure was explored by using GPS tracking devices on consenting individuals who also carried personal PM_4 monitors.

A total of five (5) different micro-environments were identified by considering where all individuals carrying GPS monitors spent most of their time in July, August and September 2013, respectively. These included, in order of importance: 1) Inside a house, 2) Directly outside a house, 3) On a dirt road, 4) On a tar road and 5) On an open field (Figure 5.11). Most of the personal movements (on average 87%) were concentrated inside and directly outside homes. Individuals spent on average 11% of their time on roads, moving between destinations within the settlement and a mere 2% of their time on open fields in transit from one destination to another. The GPS coordinate readings represented day time movement patterns ranging from 9am in the morning to 6pm in the late afternoon. No position readings were taken during the night, but it can be assumed that the individuals spent a low fraction of time outside of the household

during the evening, and spent most of their time indoors at night. People were found to spend more time indoors in colder months and conversely spent more time outdoors as months became progressively warmer (Figure 5.11).

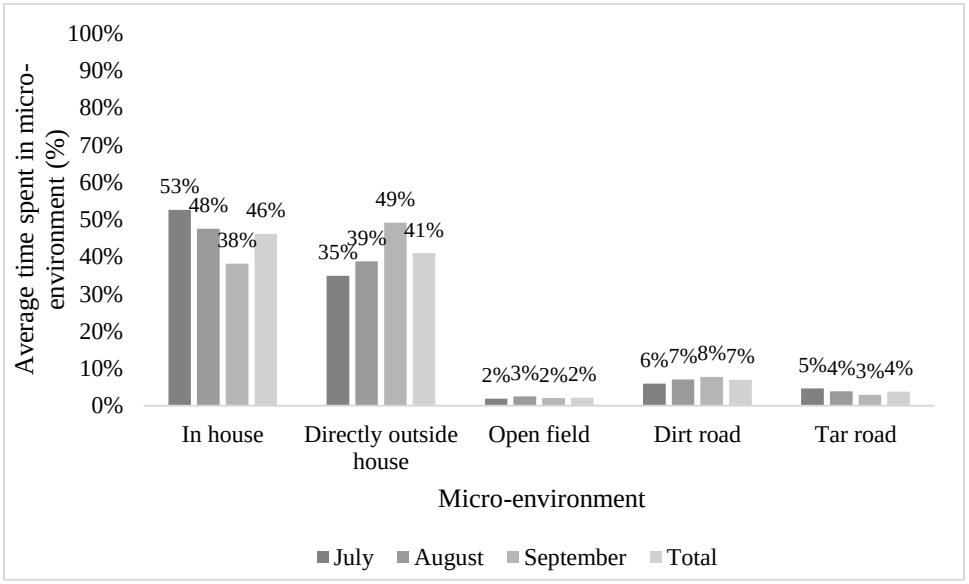


Figure 5.11. Average percentage of time spent in each micro-environment per month for which GPS measurements were collected (July n = 8831, August n = 25 193, September n = 11 909)

5.3.2 Total personal exposure: A one-individual case study

When plotting location points and corresponding PM concentrations on a SPOT 6/7 satellite image of KwaDela, it was observed that the person carrying the GPS and personal PM_4 monitors was exposed to a wide range of concentrations in every micro-environment (Figure 5.12). Here, the individual was exposed to PM_4 concentrations ranging from 36 – 2781 µg/m³ on 25 August 2013. When plotting similar figures for every other day between 21 and 28 August 2013, it was found that personal exposure concentrations in this case study were highly variable in space and time and that they did not necessarily follow a predictable trend (Table 7.1 in Appendix C). It is evident that the individual is exposed to high PM_4 concentrations throughout the day in both the indoor environment as well as in close proximity to a house, i.e. in the ambient environment.

During the time in question, the individual (a middle-aged woman), spent the majority of her time in two micro-environments whilst wearing the monitors, namely inside a house and directly outside a house. Because measurements were only taken during the day hours, it makes sense that the individual spent a large proportion of time outside (Figure 5.14). It is assumed that the night hours were mostly spent in the indoor environment, however, no data is available to substantiate this statement. It is assumed that, because the measurements taken only represent exposure concentrations between 9 am and 6 pm, that peak PM_4 concentrations, resulting during main burning periods have not been accounted for (Figure 5.13).

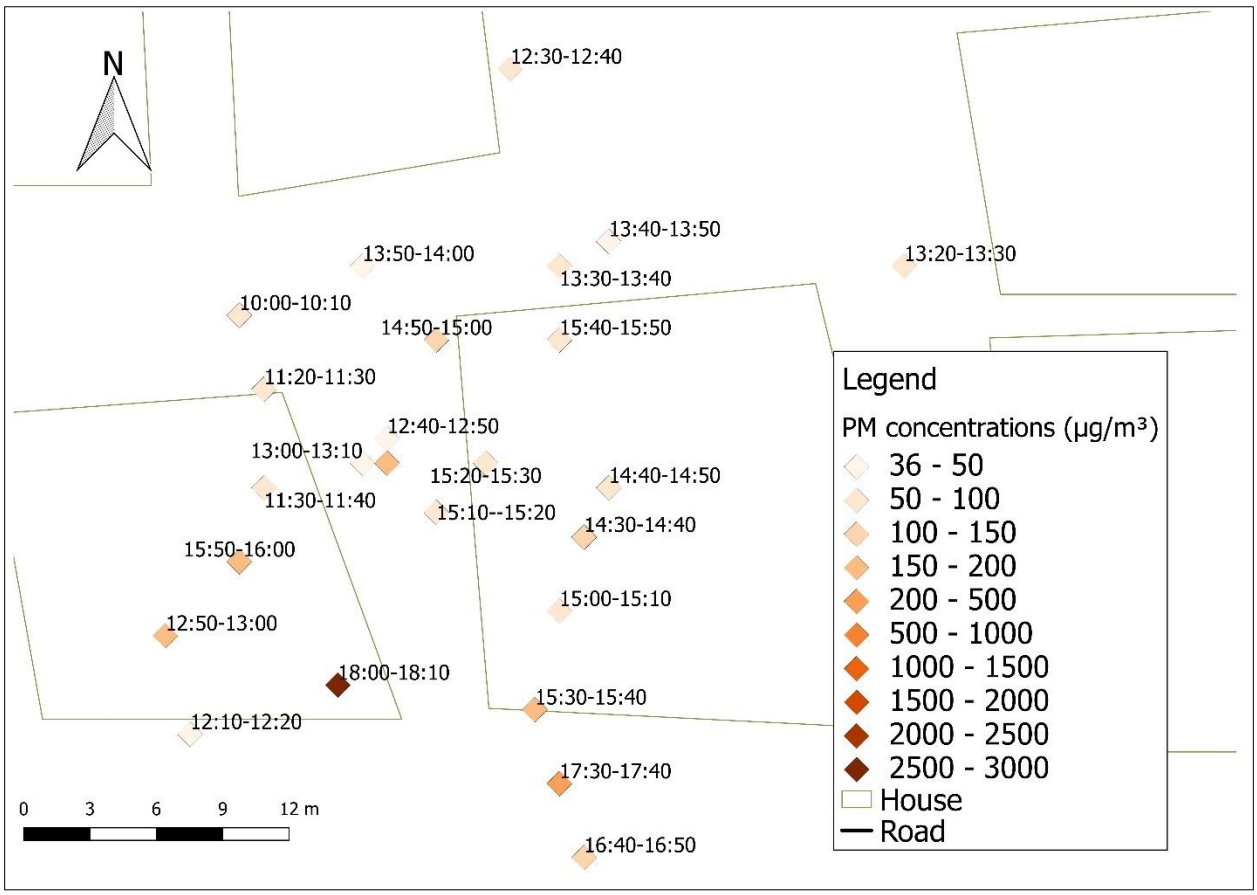


Figure 5.12. GPS tracks showing average personal PM_4 concentration exposure on the 25 August 2013. Micro-environments displayed are focused on "Inside a house" (delineated by an outlined rectangle) and "Directly outside a house" (the space outside the rectangles)

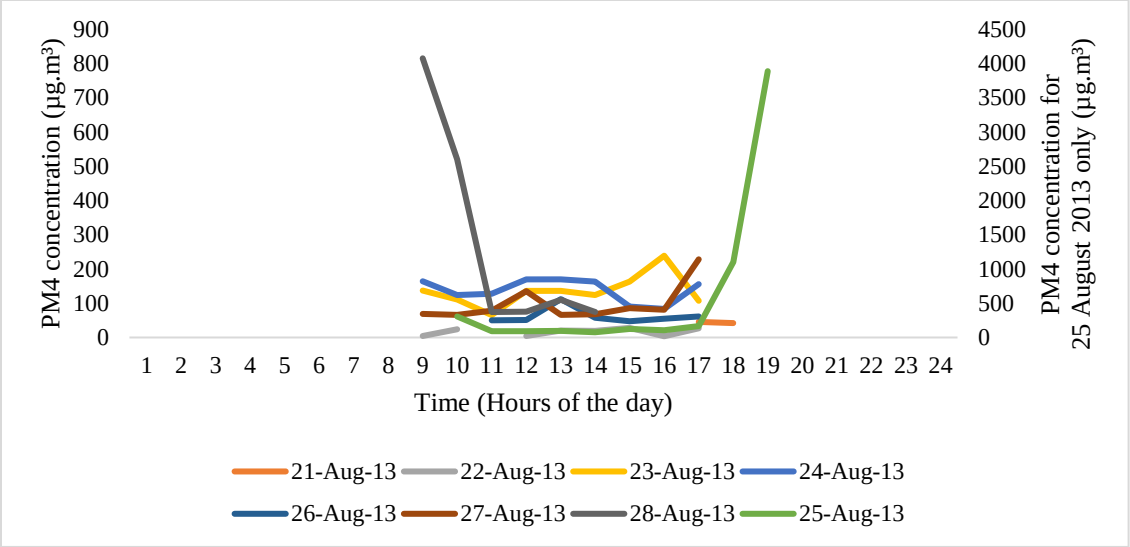


Figure 5.13. Hourly average personal PM_4 concentrations measured from 21-28 August 2013

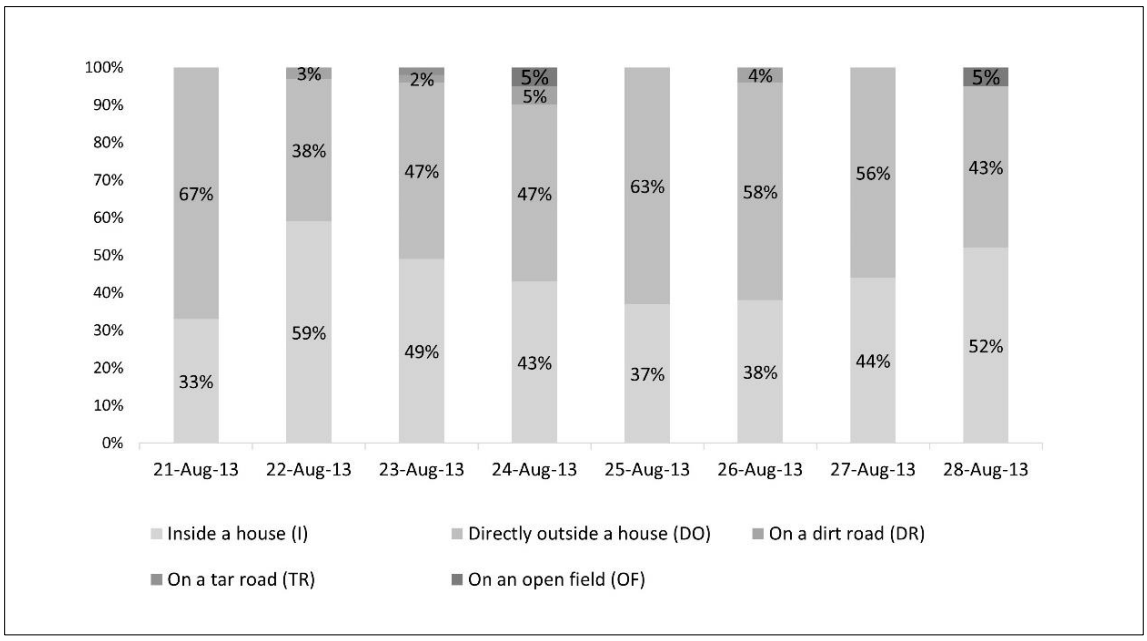


Figure 5.14. Percentage of time spent in each micro-environment per day in question by the person wearing the GPS monitor between 21 and 28 August 2013

Potential PM_4 intake doses ascertained using indirect and direct methods for the days concerned were variable (Table 5.7). Indirect, daily time-weighted integrated potential doses ranged from 0.92 mg on 26 August 2013 to 2.96 mg on 28 August 2013 (Table 7.2 in Annexure D). When considering direct potential dose derivation methods, intake doses were found to range between 0.02 mg and 0.76 mg for the time for

which measurements were available (only a few hours in the day). Highest doses corresponded to the days on which the most readings were available. It is not possible to directly compare direct and indirect results for an entire day, as there is no full 24-hour dataset for personal measurements. However, results indicate that, when comparing indirectly derived inhalation doses with directly derived inhalation doses only for the time during which personal measurements were available, it is at times underestimated what is breathed in by the individual concerned (i.e. indirectly derived doses are lower for five (5) out of eight (8) days when compared to directly derived doses).

Table 5.7. Directly and indirectly derived potential doses (mg) over a specified time period

	Indirect time-weighted potential dose for the entire day		Indirect time-weighted potential dose for the hours in which personal measurements were available		Direct potential dose	
Date	Dose (mg)	Time (hours)	Dose (mg)	Time (hours)	Dose (mg)	Time (hours)
21-Aug-13	1.50	24.00	0.02	1.00	0.02	1.00
22-Aug-13	2.89	24.00	0.08	4.83	0.05	4.83
23-Aug-13	2.10	24.00	0.03	7.17	0.52	7.17
24-Aug-13	1.49	24.00	0.14	3.50	0.21	3.50
25-Aug-13	1.98	24.00	0.35	5.83	0.76	5.83
26-Aug-13	0.92	24.00	0.25	4.33	0.19	4.33
27-Aug-13	1.30	24.00	0.14	2.67	0.17	2.67
28-Aug-13	2.96	24.00	0.23	3.50	0.34	3.50

Above it was ascertained how much PM is breathed in by the concerned individual during specified time periods. The resulting figures are representative of doses of PM inhaled during winter as a result of time spent exposed to PM_4 in the ambient and the indoor environment. Though indirectly derived daily doses listed here fall below what has been demonstrated to be breathed in in other low-income communities (e.g. when compared to potential inhalation doses in Bangladesh where doses ranged between 4.4mg and 5.8mg of $PM_{2.5}$ per day (Chowdhury et al., 2012)), it should be kept in mind that, particularly for smaller PM size fractions, no threshold exists that does not cause a discernible health effect. Additionally, it is very likely that the directly ascertained total daily dose intake fraction of the individual would in fact be much higher than what has been demonstrated by means of indirect derivation methods as presented here, as peak exposure concentrations during burning times have not been included, and most notably because the

direct doses have been ascertained with an incomplete dataset. It remains to be said that this exercise showed how an individual in a low-income community context is directly exposed to PM concentrations that by far exceed ambient standards in numerous micro-environments, and this leads to unacceptably high potential doses of PM being inhaled.

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This chapter discussed whether larger scale PM characterisation trends are also evident at a household scale. As part of this, regression analyses were conducted to ascertain whether there are any clear relationships to be found when considering ambient, indoor and personal PM concentrations at a *case* and at a community level. A one-individual case study was also presented, illustrating the concentrations to which an individual was exposed in specific micro-environments and what dose of PM was inhaled over different timeframes.

The next chapter represents the final chapter of this study, which outlines the main conclusions that can be drawn from the results presented herein.

Chapter 6 Summary and conclusions

It was the intention of this study to characterise ambient, indoor and personal PM concentrations of different size fractions in two low-income communities on the Mpumalanga Highveld: KwaDela and KwaZamokuhle. Data used was collected between 2013 and 2016 as part of Sasol and Eskom's air quality offset pilot studies. Relationships between ambient, indoor and personal PM concentrations were investigated. Personal exposure to PM concentrations was assessed by considering a one-individual case study.

Main findings are summarised in this chapter and they are relevant to the assessment of whether centrally localised ambient stations which are used to draw compliance and epidemiological conclusions in such communities, represent what people actually breathe. This is relevant for air quality management strategies in low-income communities on the Highveld.

Air pollution has been identified as one of the leading causes of global disease burden, and this most particularly in low-income communities around the world (Cohen *et al.,* 2017; Rosenthal *et al.,* 2017). Studies conducted in low-income communities in South Africa support these findings, and, significantly relevant for this study, it has been found that residential combustion activities have been singled out to represent the greatest source of air pollution in low-income communities on the Mpumalanga Highveld (Engelbrecht *et al.,* 2000; Engelbrecht *et al.,* 2002). PM concentrations measured in such communities have been shown to exceed NAAQS limit values (Mdluli, 2007), and observed relationships between air pollution and morbidity and mortality have been demonstrated (Terblanche et al. 1992a; Wichmann, 2006).

As research may be termed one of the most important tools that can be used to provide a foundation for action geared towards public health improvement, it is the purpose of this study to help understand how PM concentrations in two low-income communities on the Mpumalanga Highveld are characterised by larger- and local-scale factors and how this influences variability and relationships between ambient, indoor and personal measured concentrations. This is of great importance when understanding personal exposure to PM concentrations in such communities, in particular where compliance and epidemiological related statements are made, using data collected at a sole stationary ambient monitoring station.

Ambient, indoor and personal PM concentrations were measured in KwaDela and KwaZamokuhle between 2013 and 2016 as part of Sasol and Eskom's air quality offset pilot studies. The data collected in these campaigns was used to characterise PM concentrations within and between these two low-income communities by considering seasonal, temporal and socio-economic factors. Empirical relationships between ambient, indoor and personal PM concentrations were identified by means of regression analyses and ratios and total personal exposure was assessed by dissecting a one-individual case study, in which simultaneously collected personal PM_4 concentrations and GPS location data were interpreted. The below sections list the main findings per research objective.

6.1 Characterising particulate matter concentrations In KwaDela and KwaZamokuhle

Ambient, indoor and personal PM concentrations were measured in KwaDela and KwaZamokuhle communities between 2013 and 2016. Comparative statements were made to explain what PM concentrations in KwaDela and KwaZamokuhle look like in different seasons of the year and different times of the day. Daily, hourly as well as maximum concentrations were considered for the purposes of this exercise. Main findings are:

1. Air quality in KwaDela and KwaZamokuhle is unacceptably poor, especially so in winter months, when NAAQS are exceeded most of the time.

2. Ambient daily average winter PM_{10} and $PM_{2.5}$ concentrations in both KwaDela and KwaZamokuhle were found to be on average, twice as high as summer PM concentrations.

3. NAAQS were exceeded in spring, summer and winter, with most exceedances occurring in the winter time.

4. Indoor and personal daily PM_4 concentrations were up to three (3) times higher in winter than in summer in both communities.

5. Indoor PM concentrations are typically higher than ambient PM concentrations, particularly so during peak burning periods and this effect is exacerbated in colder months.

6. Indoor and personal daily average and hourly maximum PM_4 concentrations were on average higher in KwaZamokuhle than in KwaDela, except in summer.

7. Hourly maximum indoor and personal PM concentrations were higher in winter than in summer in both communities.

8. A pronounced bimodal diurnal pattern was identified when plotting overall hourly average time-series graphs for ambient PM measurements in both KwaDela and KwaZamokuhle pointing to peak concentrations during main burning times in the morning and the late afternoon/ evening. Winter peaks were more pronounced than summer peaks.

9. The variation of daily and hourly maximum concentrations around the respective PM type mean values was generally high within and across the communities, however, it was higher in spring than in summer, and highest in winter.

10. Results found at a community level were evident at a household level where: 1) Winter average PM concentrations were higher than summer concentrations. 2) PM concentrations were highly variable in space and time. 3) Indoor PM measurements were higher than ambient PM measurements.

6.2 The relationships between ambient, indoor and personal PM concentrations in KwaDela and KwaZamokuhle

Simultaneously collected hourly average ambient, indoor and personal PM measurements were log normally transformed and compared by means of regression analysis. It was identified whether or not discernible relationships between ambient, indoor and personal PM concentrations were evident. Relevant ratios were determined. Main findings that unpack this objective are:

11. Overall, no clear discernible relationship trends could be found between PM concentrations measured at different monitoring sites, be this at a community or a household level.

12. However, out of all PM type regression combinations, the variability in indoor hourly average measurements was most likely to explain the variability of the personal hourly average concentrations, and this in particular in the winter time, when most people spend more of their time in the indoor environment. This is supported by the finding that indoor and personal PM concentrations are most likely to correspond in the winter time (i.e. indoor: personal PM_4 ratio was most likely to be 1 during winter and less so during summer).

13. High variability of PM concentrations in space and time made it difficult to identify clear relationships between the different PM types.

14. Indoor PM_4 concentrations are generally higher than ambient concentrations, this even in some households that do not conduct domestic burning activities, pointing to the fact that pollution infiltration into the indoor environment is a major contributor to indoor air pollution.

6.3 Personal exposure to particulate matter concentrations in KwaDela

GPS tracking data and personal PM_4 measurements taken between 21 and 28 August 2013 were paired at ten-minute average intervals. By plotting these datasets onto an aerial photograph of KwaDela using QGIS 2.14.1, total time-activity patterns helped understand personal PM exposure per micro-environment. Here main findings could be summarised as:

15. Five micro-environments within which individuals spend their time were identified in KwaDela: 1) Inside a house, 2) Directly outside a house, 3) On a dirt road, 4) On a tar road and 5) In an open field.

16. Most individuals who carried GPS monitors spent on average 90% of their time in and around a household. Less time was spent in roads and open fields.

17. Exposure to highest concentrations could not be pinpointed to the indoor environment only, as extreme personal PM measurements were also recorded when the individual carrying the GPS

monitor was in the ambient environment, however, most extreme exposure concentrations were recorded in the indoor environment and directly outside of houses.

18. Dose intake rates calculated in an indirect manner using stationary monitoring data seemed to underestimate actual intake rates, as illustrated when considering dose rates calculated form direct personal exposure measurements.

6.4 Conclusion

An unprecedentedly rich dataset was used for the purposes of this research study. In no other South African study have there been as many simultaneously measured ambient, indoor and personal PM readings that span across numerous seasons and in two different communities. It was found that air quality in KwaDela and KwaZamokuhle is extremely poor throughout the year, and that air pollution levels are particularly poor in winter months. This confirms assumptions made, that KwaDela and KwaZamokuhle, just like many other low-income communities situated on the Mpumalanga Highveld, are plagued by air pollution levels that have a significant impact on the health and well-being of the concerned population. Findings further indicate that, regardless of the location of such a low-income community, the socio-economic factors in the respective location have a determining role to play in defining the air that people breathe.

PM concentrations in the indoor environment were more often than not found to be higher than ambient PM concentrations, often reaching into the mg/m^3 range during peak burning times. This points to acute exposure events that have been shown to represent a major contributor to respiratory and cardiovascular diseases (South Africa, 2017). The results of this study emphasise the importance of considering indoor air pollution levels alongside ambient levels when conducting epidemiological studies concerning the health impact of air pollution in low-income communities and when developing air quality management plans. In support of this notion, soon to be published indoor air quality guidelines will include indoor PM limit values, which aim to ensure that when a specific threshold of PM levels is exceeded indoors, this acts as a catalyst to call for action targeted towards the implementation of household-level interventions to reduce indoor air pollution (South Africa, 2017). The fact that the PM levels in some of the houses in this study were at times lower than ambient PM concentrations shows that it is indeed possible for indoor

concentrations to be lower than ambient concentrations and that it is possible to reduce indoor PM concentrations to safe breathing levels with the correct mitigation strategy.

It follows on from the above stated that, because ambient, indoor and personal PM levels measured during this research study have been shown to be highly variable in space and time, epidemiologists should heed that indirect personal exposure assessments need to be carefully conducted. Optimally, when conducting exposure assessments in a low-income community setting, personal measurements should be used to calculate personal exposure concentrations and resulting dose intake fractions, as averaged readings stemming from stationary monitors alone will not render adequate results as they do not take into account this variability. Time-activity pattern data collected in this study showed that individuals spent most of their time inside or directly outside of a household. This means that the air quality in and directly outside of the household mostly determined the personal exposure concentrations of an individual. A centrally located ambient monitoring station situated at a school or a church, as was the case in KwaDela and KwaZamokuhle, is then evidently not a true representation of what people are breathing, as it doesn't take into account the "household" air pollution, which represents the air directly inside and in close proximity to a household.

In conclusion, this research recommends that compliance and epidemiologically inclined statements should express caution when using PM concentrations measured at stationary ambient monitoring stations as a proxy for personal exposure as PM concentrations in a low-income community context are non-homogenous in space and time. Though using data measured at a single monitoring site may be useful when trying to understand chronic health effects associated with long-term exposure to suspended particles, this study shows that these measurements will most certainly only be of limited use when trying to understand acute exposure and this could lead to "exposure misclassification" (Wilson, 2006). Total acute and chronic exposure can best be defined by considering ambient, indoor and personal measurements simultaneously, and this information should be heavily supported by socio-economic data for contextualisation. If this holistic approach is taken into account, air quality management strategies will go far in making the air quality in low-income communities safer to breathe.

Project Funding

This research study is funded by North West University.

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Chapter 7Annexures

7.1 Annexure A – Hourly maximum concentrations measured per *case* in KwaDela and KwaZamokuhle per campaign

The maximum hourly value for each day for which measurements existed was derived and plotted for every PM type for every *case* for every seasonal sampling campaign. Indoor and personal hourly maximum PM concentrations were, where possible, compared to the maximum hourly value concentrations for the same hour of the day for ambient PM concentrations. Indoor and personal PM_4 measurements do not exist for every house for every season, and hence not every graph shown in this section of the report will display results for the same set and the same number of houses. The terms "house" and "*case*" may be used interchangeably in this section.

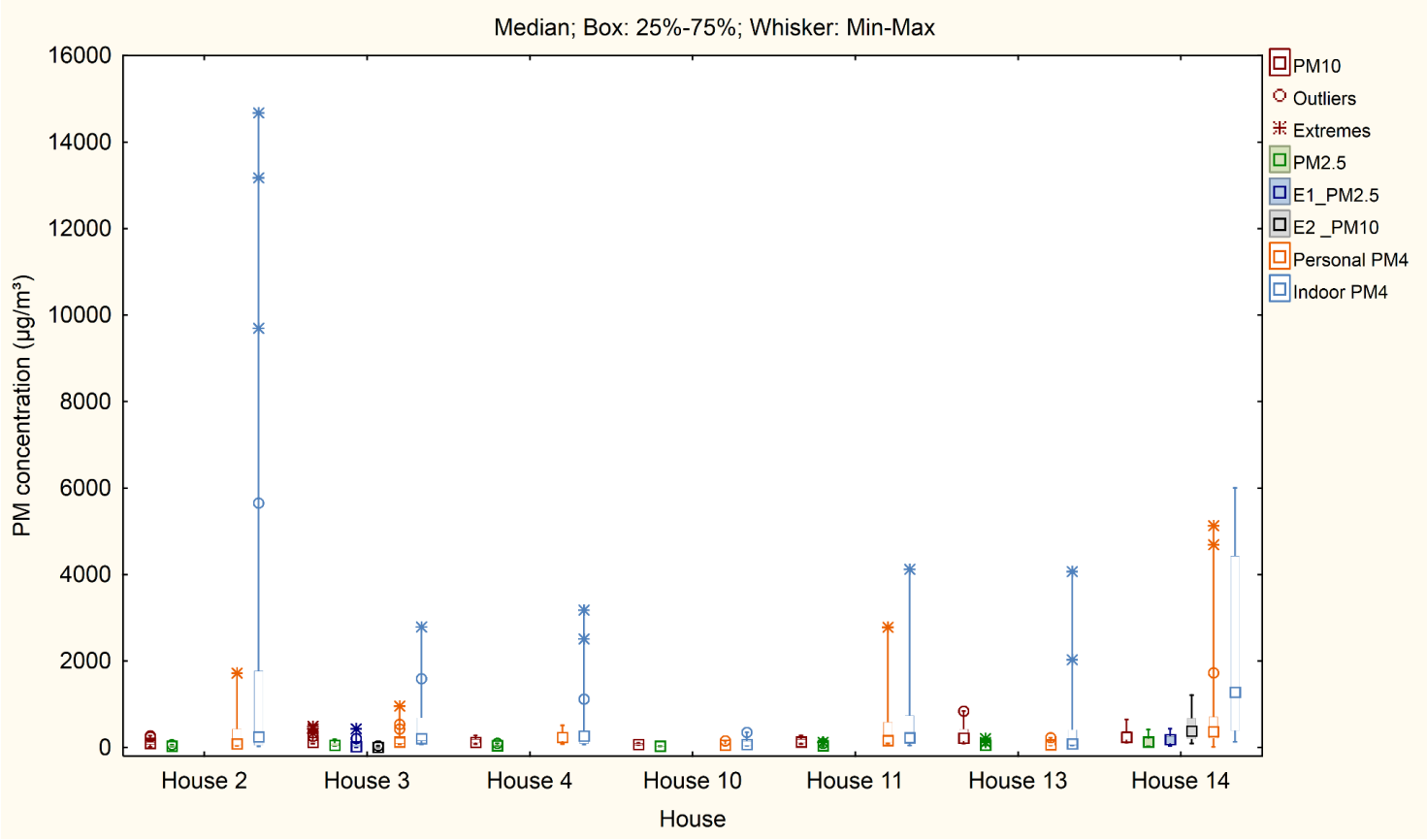

Figure 7.1. Hourly maxima per PM type compared at household level KwaDela Winter 2013

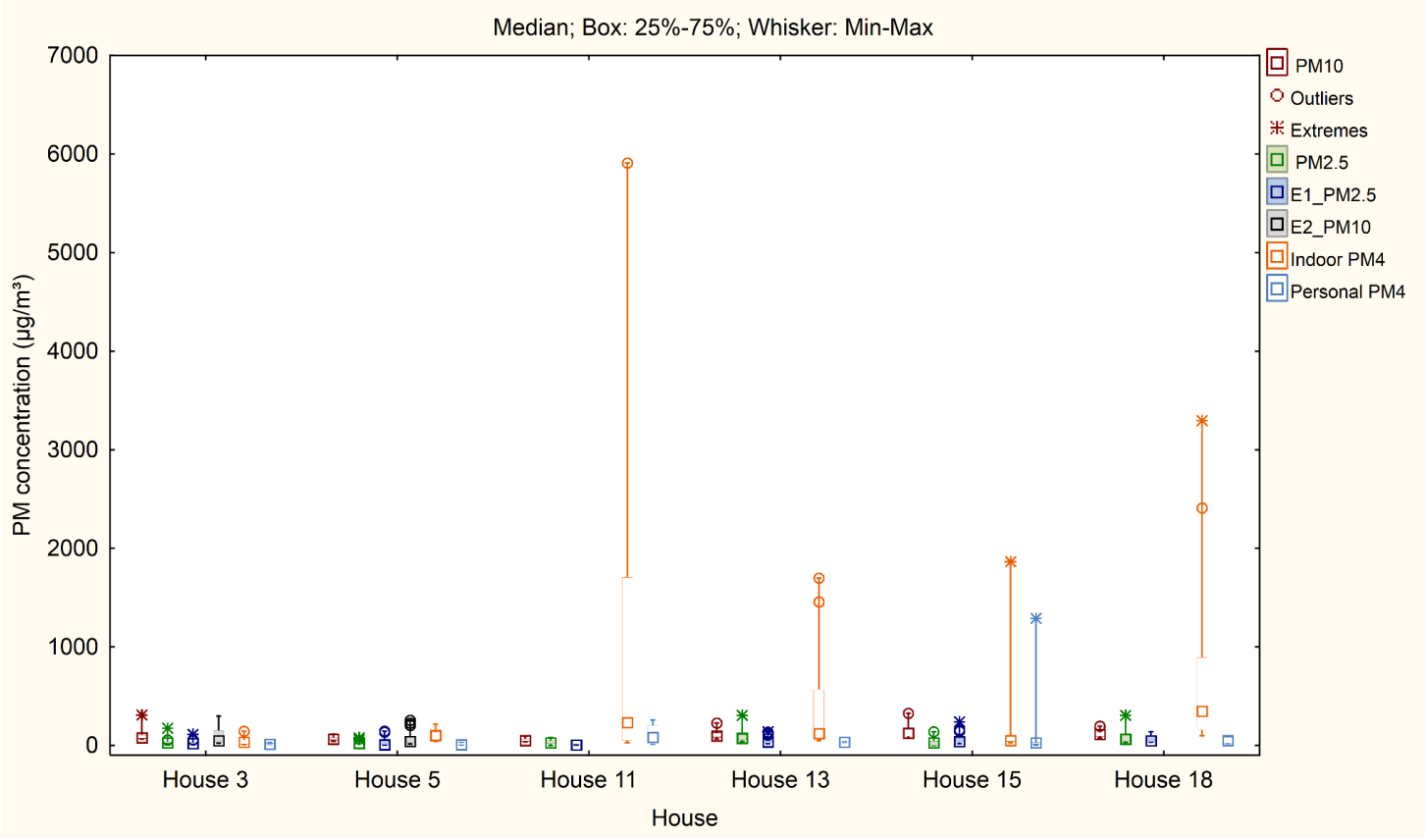

Figure 7.2. Hourly maxima per PM type compared at household level KwaDela Summer 2014

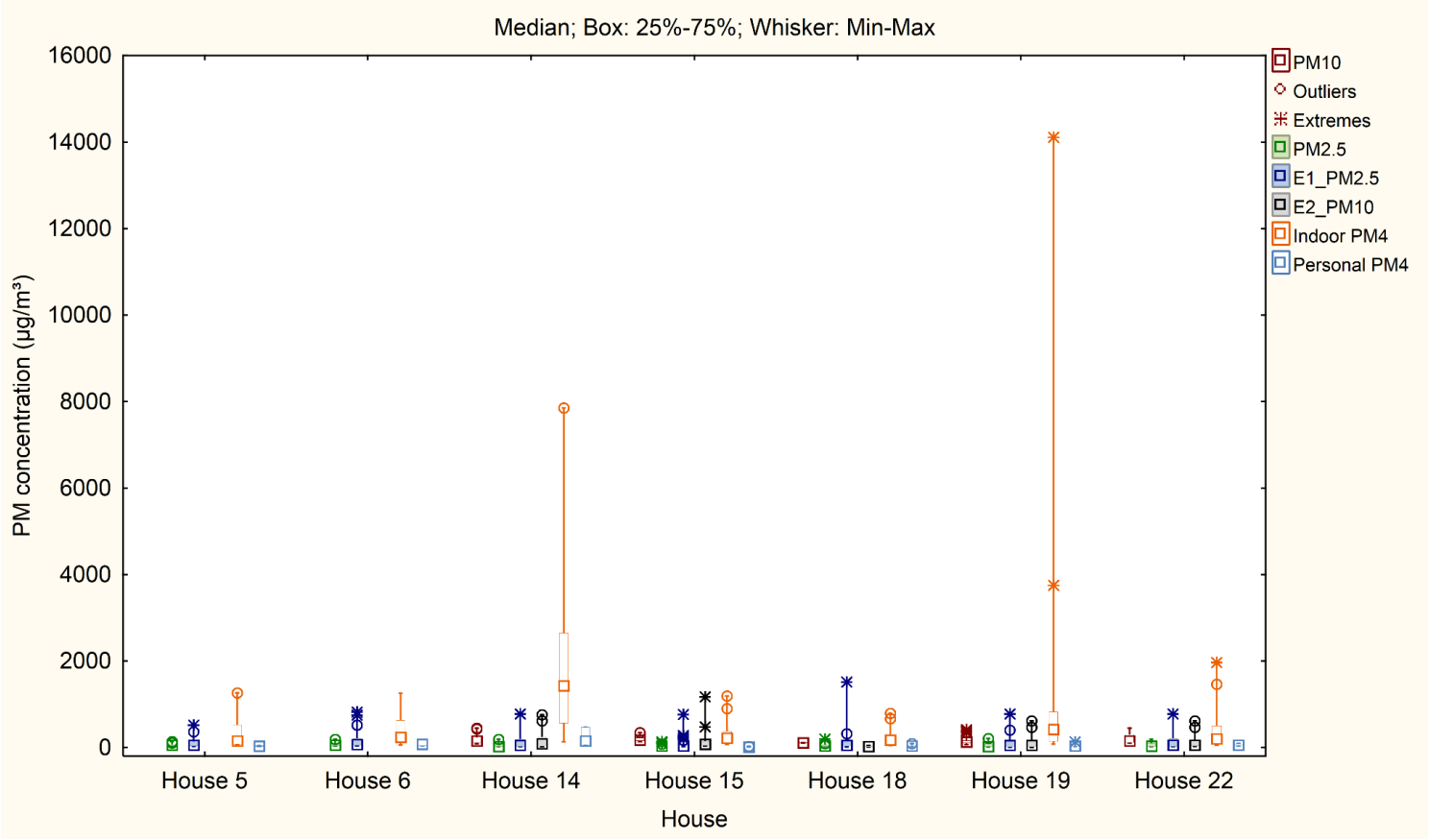

Figure 7.3. Hourly maxima per PM type compared at household level KwaDela Winter 2014

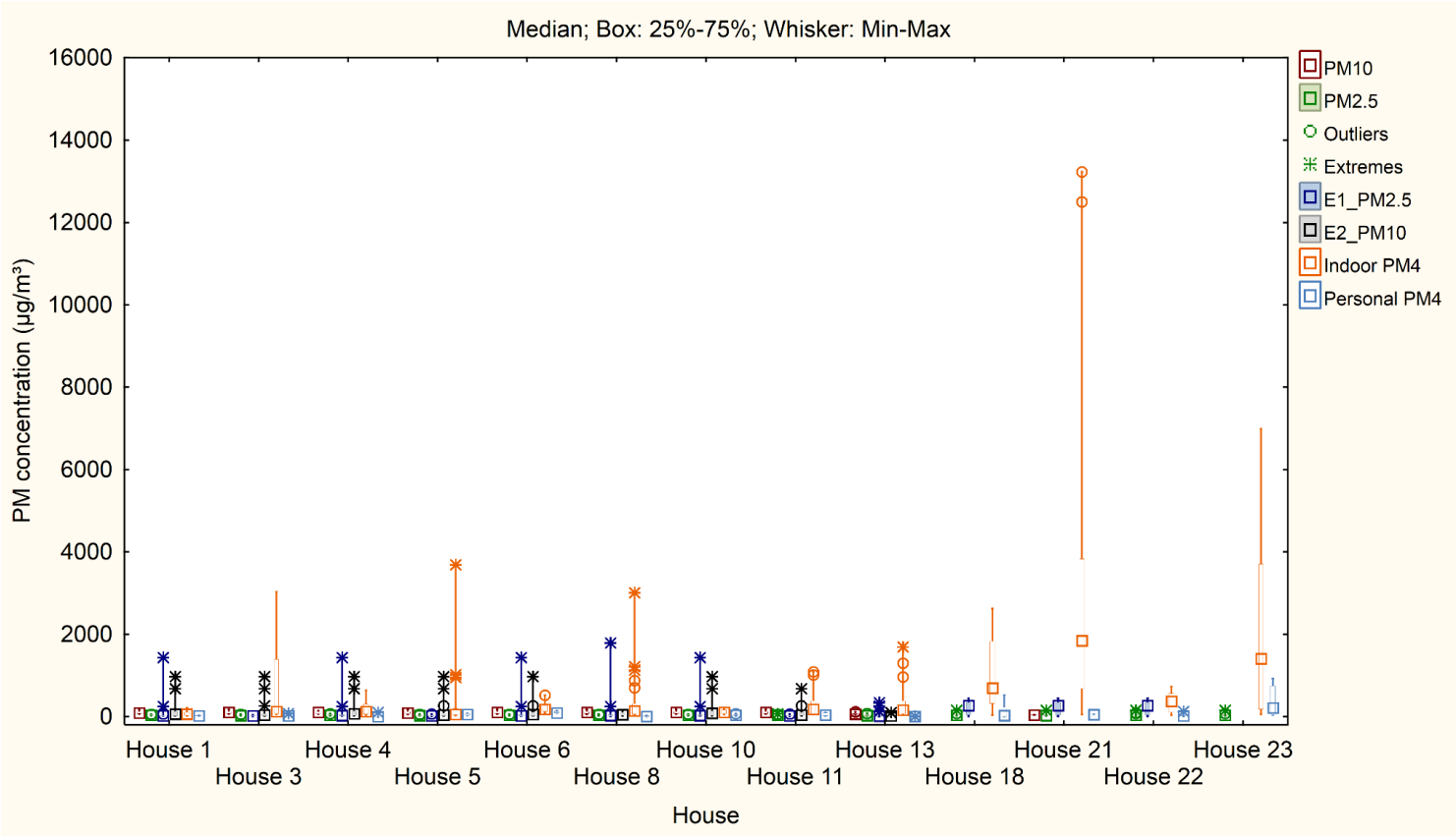

Figure 7.4. Hourly maxima per PM type compared at household level KwaDela Summer 2015

Figure 7.5. Hourly maxima per PM type compared at household level KwaZamokuhle Spring 2015

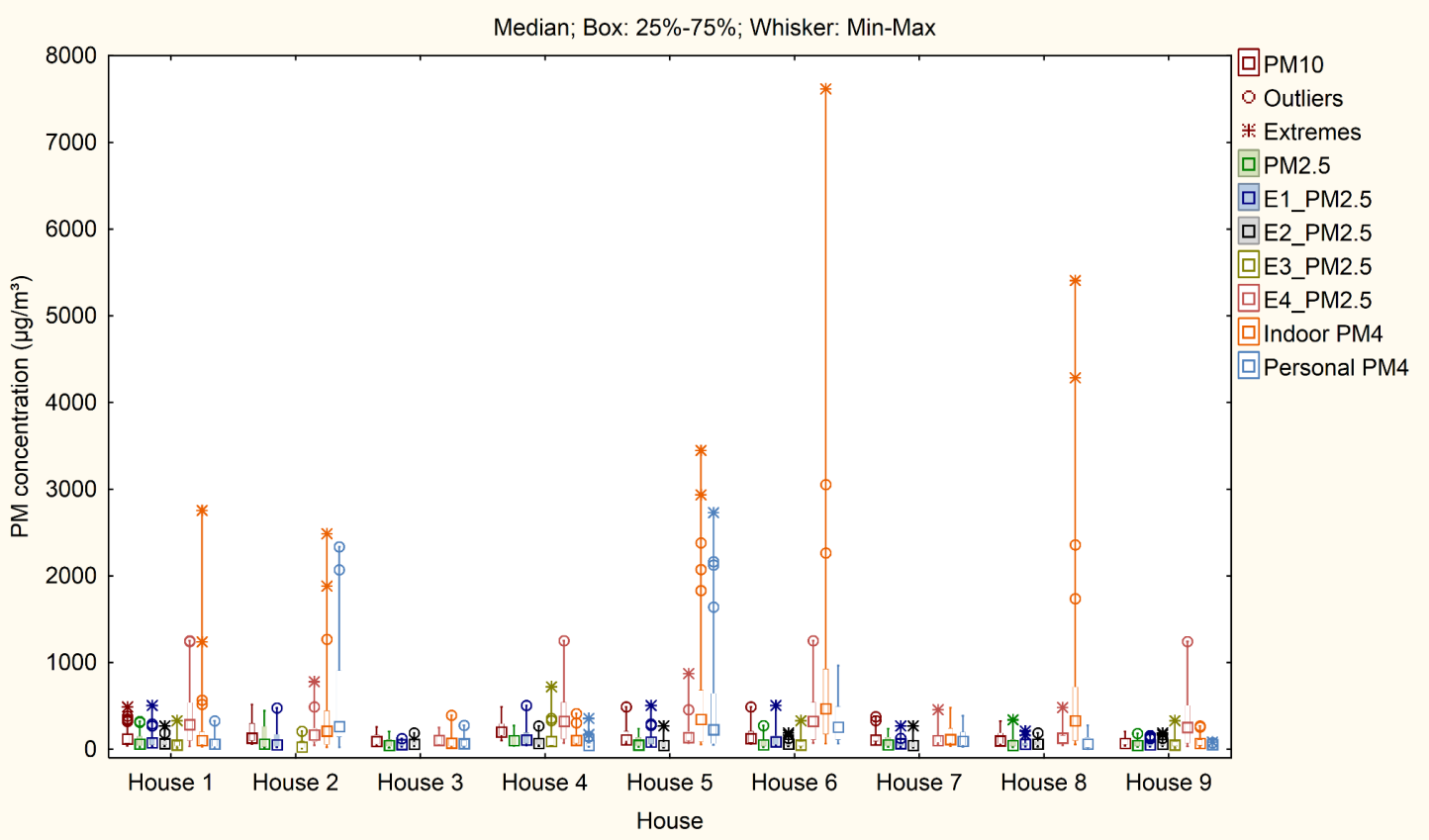

Figure 7.6. Hourly maxima per PM type compared at household level KwaZamokuhle Summer 2016

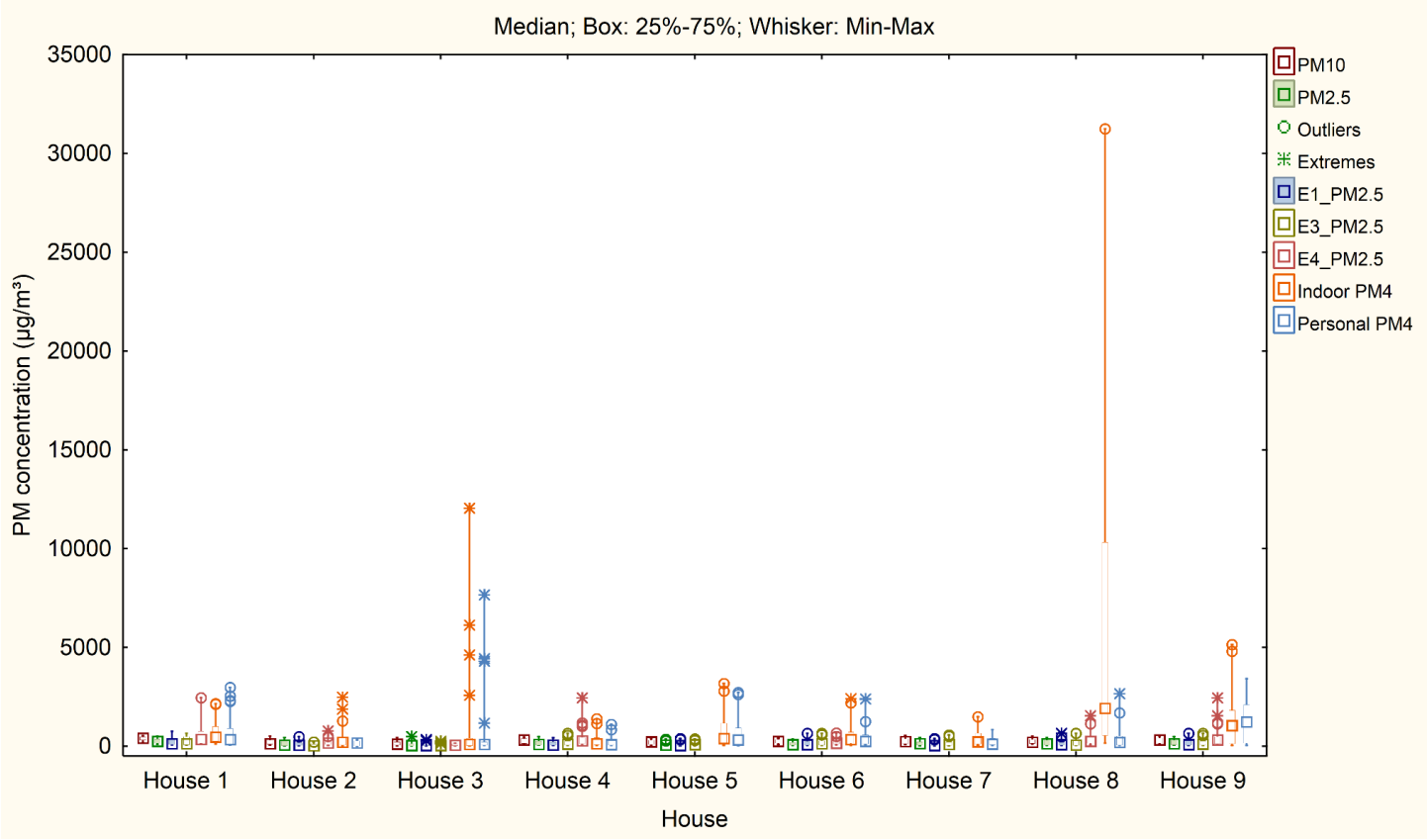

Figure 7.7. Hourly maxima per PM type compared at household level KwaZamokuhle Winter 2016

7.2 Annexure B – Regression analyses between ambient, indoor and personal PM concentrations at a community level

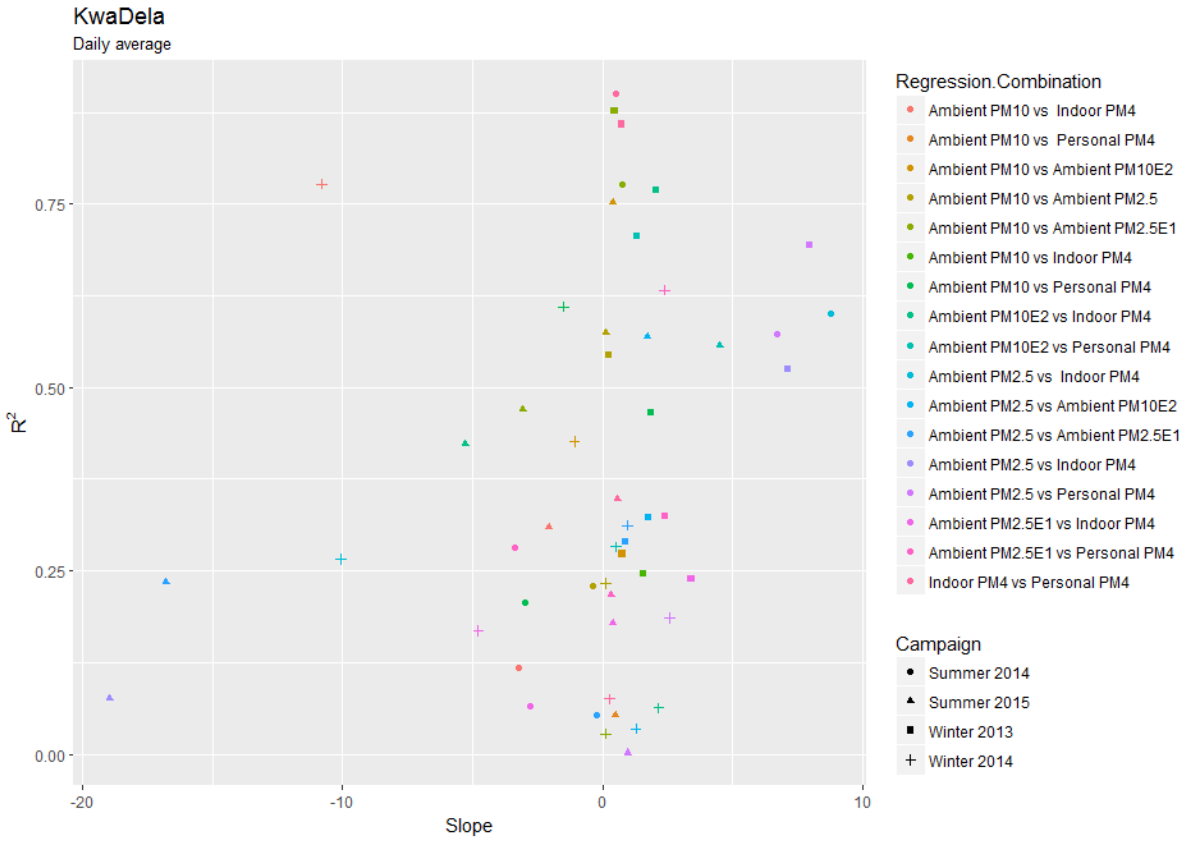

Figure 7.8. Scatter plot showing the R^2 value of a regression analysis against the slope of the line of that same regression analysis when plotting overarching, community-level daily average particulate matter concentrations in KwaDela

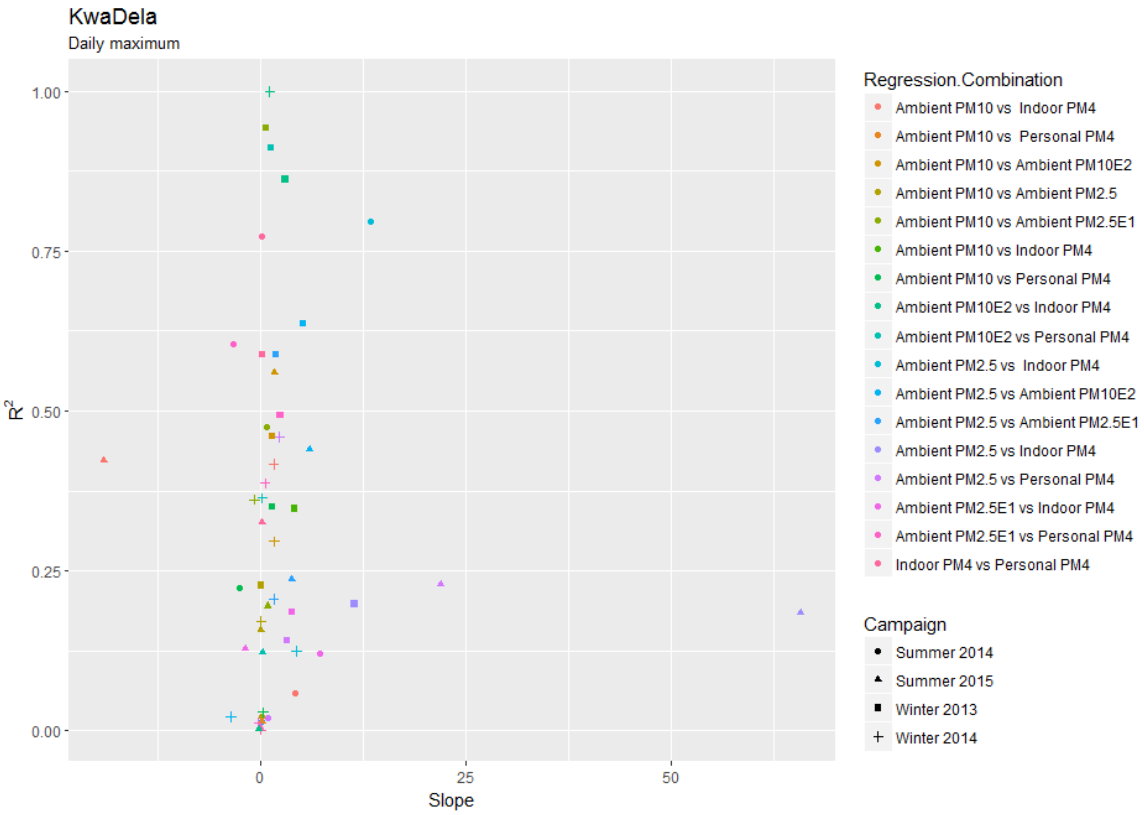

Figure 7.9. Scatter plot showing the R^2 value of a regression analysis against the slope of the line of that same regression analysis when plotting overarching, community-level daily maximum particulate matter concentrations in KwaDela

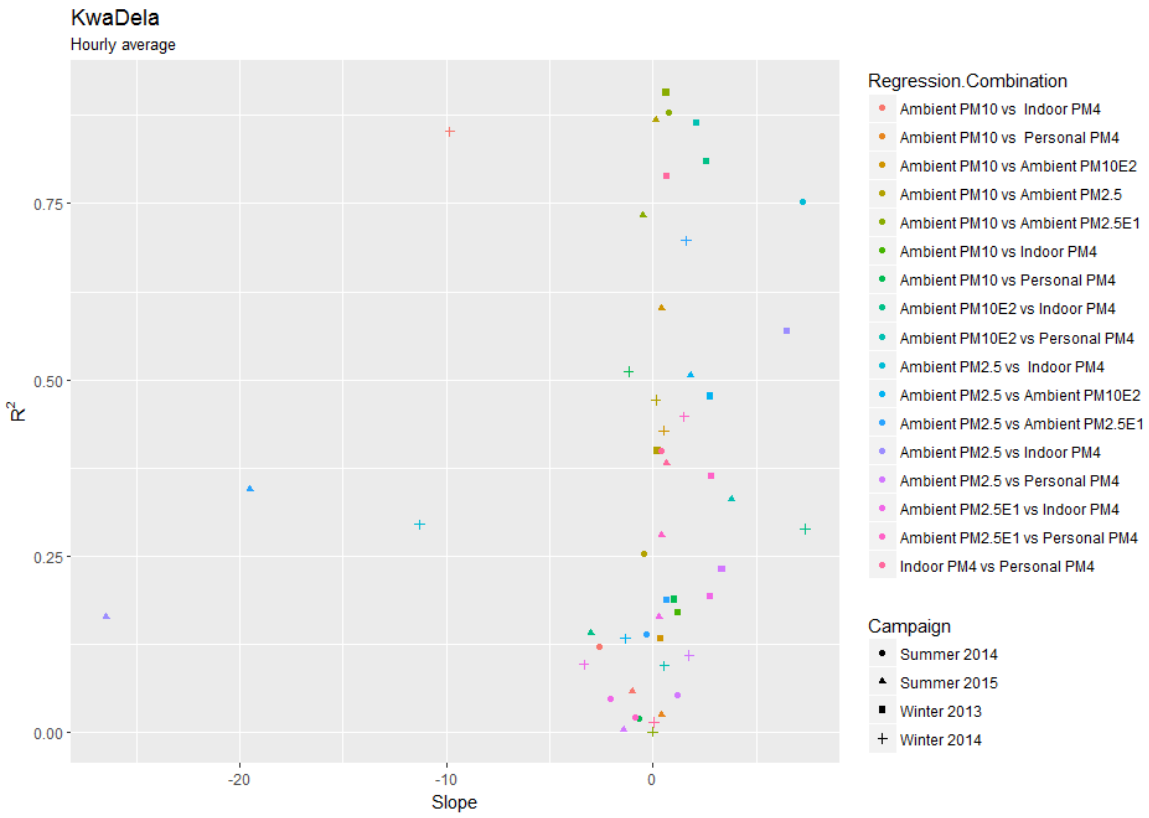

Figure 7.10. Scatter plot showing the R^2 value of a regression analysis against the slope of the line of that same regression analysis when plotting overarching, community-level hourly average particulate matter concentrations in KwaDela

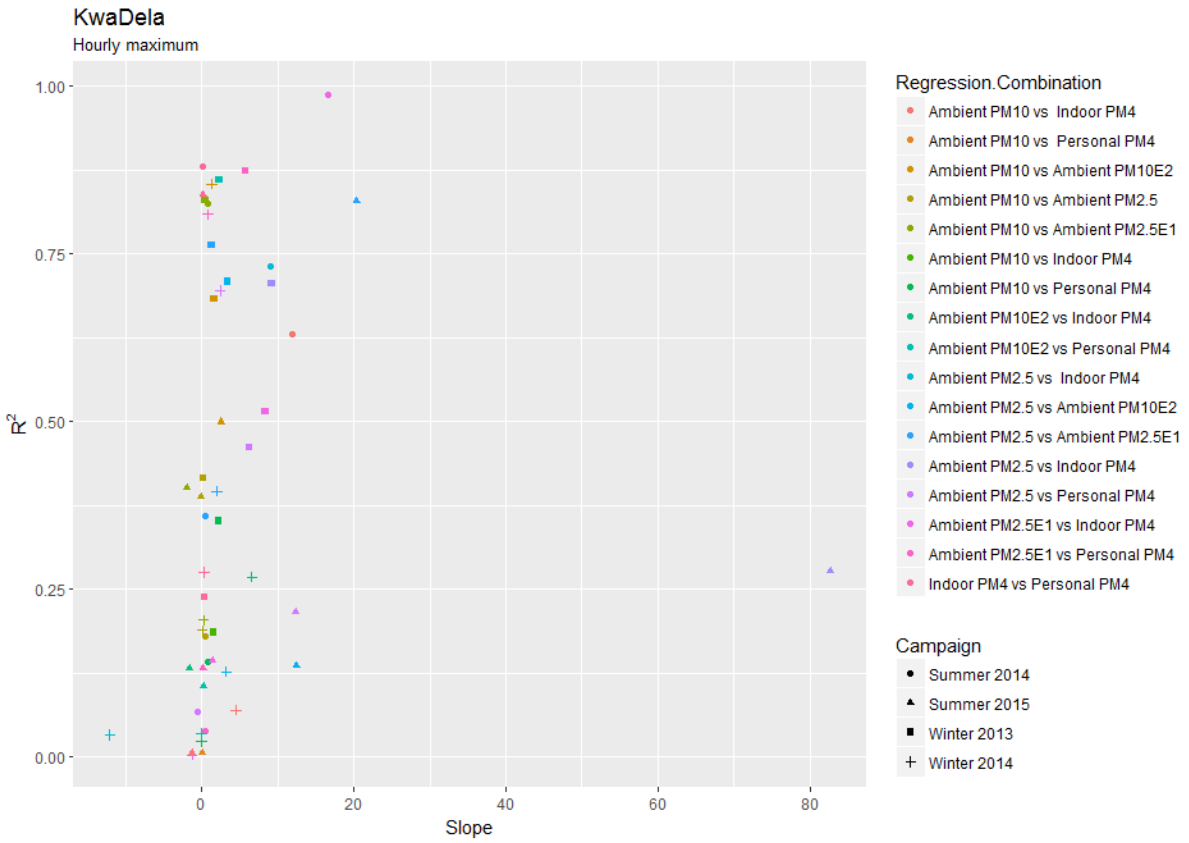

Figure 7.11. Scatter plot showing the R^2 value of a regression analysis against the slope of the line of that same regression analysis when plotting overarching, community-level hourly maximum particulate matter concentrations in KwaDela

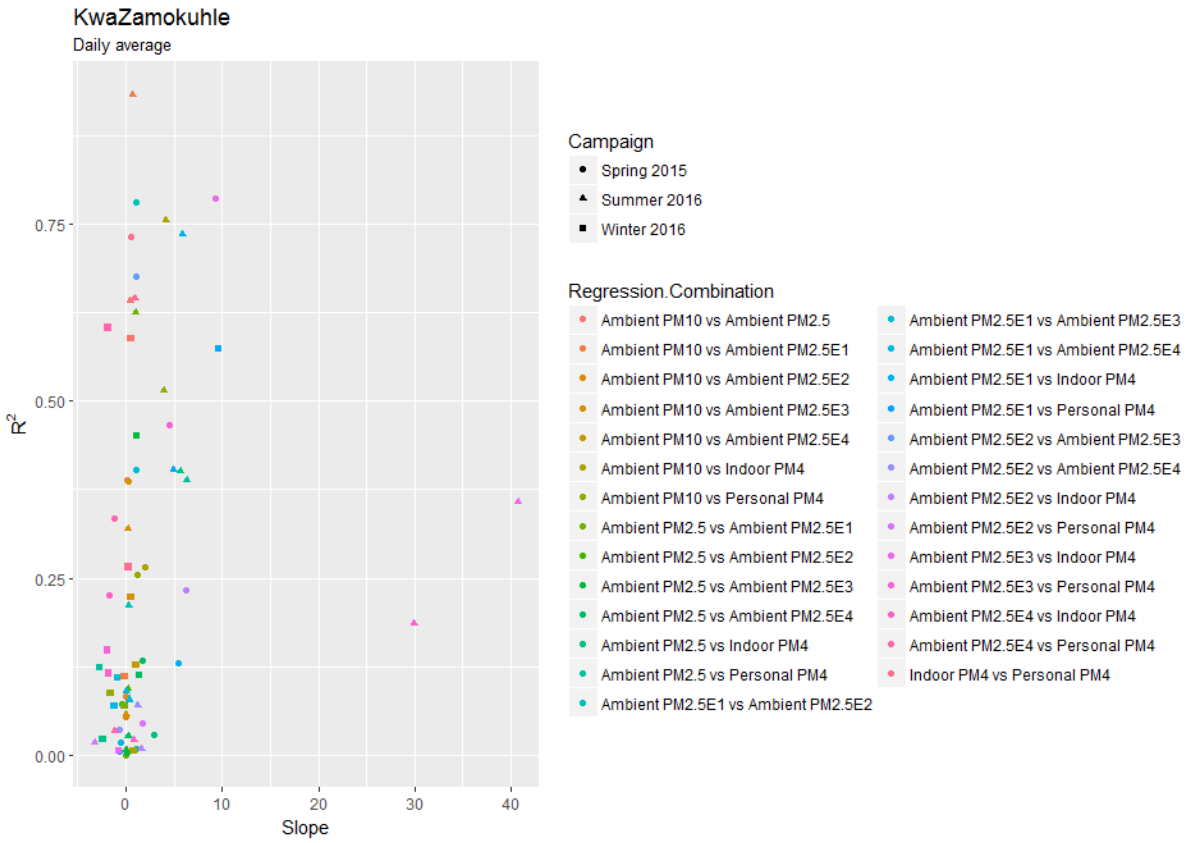

Figure 7.12. Scatter plot showing the R^2 value of a regression analysis against the slope of the line of that same regression analysis when plotting overarching, community-level daily average particulate matter concentrations in KwaZamokuhle

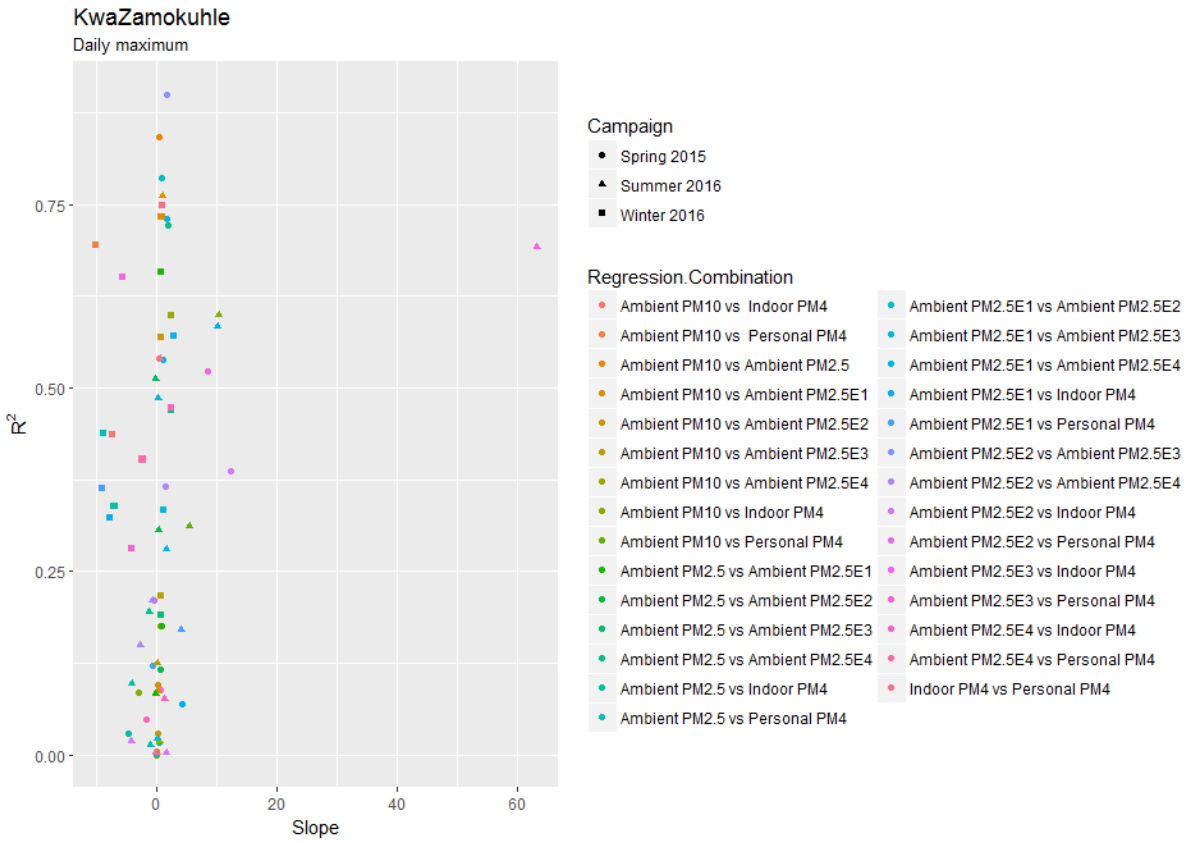

Figure 7.13. Scatter plot showing the R^2 value of a regression analysis against the slope of the line of that same regression analysis when plotting overarching, community-level daily maximum particulate matter concentrations in KwaZamokuhle

Figure 7.14. Scatter plot showing the R^2 value of a regression analysis against the slope of the line of that same regression analysis when plotting overarching, community-level hourly average particulate matter concentrations in KwaZamokuhle

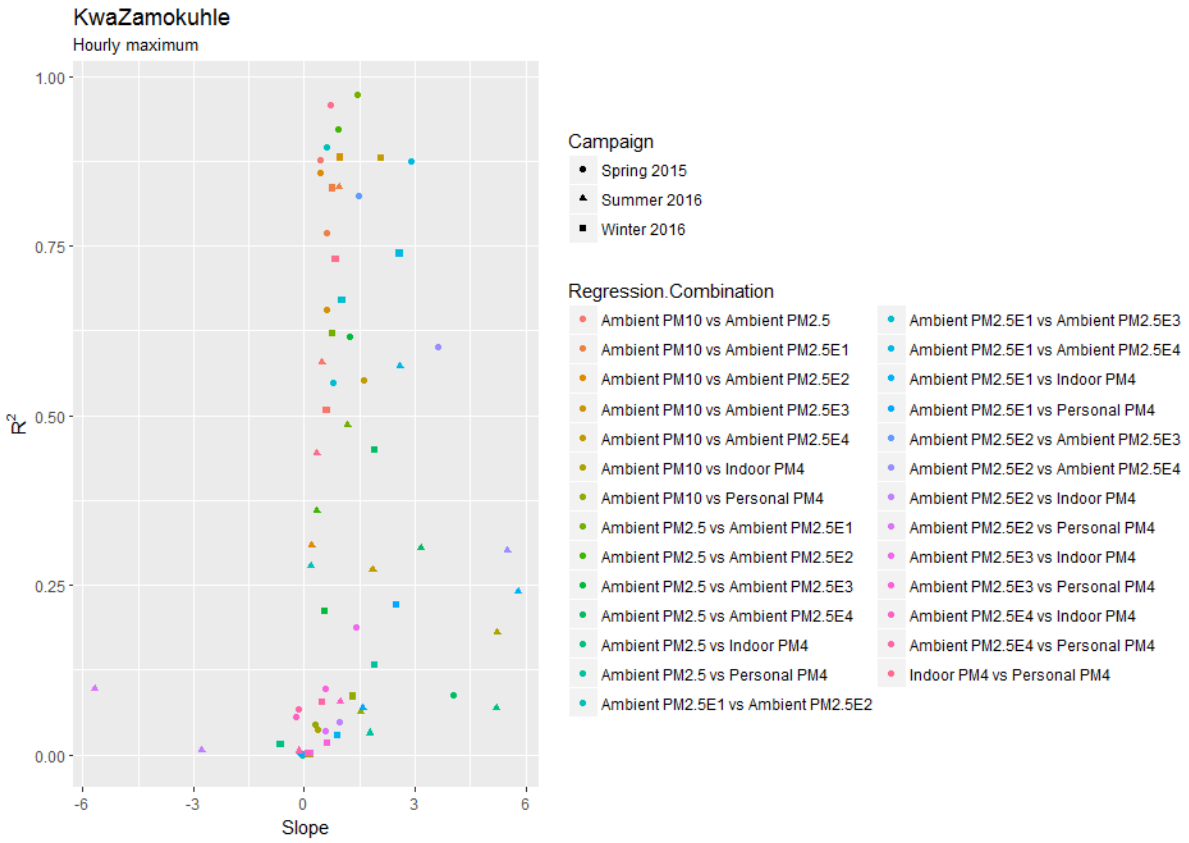

Figure 7.15. Scatter plot showing the R^2 value of a regression analysis against the slope of the line of that same regression analysis when plotting overarching, community-level hourly maximum particulate matter concentrations in KwaZamokuhle

7.3 Annexure C – Overview of personal PM_4 concentrations measured per micro-environment

Table 7.1. Overview of personal PM4 concentrations measured per micro-environment (M-E) identified between 21 August 2013 and 28 August 2013 (I=Inside a house; DO=Directly outside a house; DR=On a dirt road; TR=On a tar road; OF=On an open field)

	21 August 2013		22 August 2013		23 August 2013		24 August 2013		25 August 2013		26 August 2013		27 August 2013		28 August 2013	
Average time	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**
8:30-8:40															148.72	DO
8:40-8:50															1441.44	DO
8:50-9:00					108.68	DO									158.73	DO
9:00-9:10			2.86	DO	88.66	I							50.77	DO		
9:10-9:20			3.58	O	76.51	DO	114.40	DO					50.77	DO	148.72	I
9:20-9:30			3.58	I	96.53	DO	87.95	DO					45.76	DO		
9:30-9:40			4.29	DO	127.27	I										
9:40 - 9:50			64.35	I	85.80	TR									56.49	I
9:50-10:00					35.04	I			699.99	I					53.63	I
10:00-10:10					38.61	DO			62.92	I					52.20	I
10:10-10:20													49.34	DO		
10:20-10:30											50.05	DO	65.78	DO		
10:30-10:40					37.90	I					50.05	DO				
10:40-10:50					37.90	I									56.49	I
10:50-11:00					67.21	DR									53.63	DO
11:00-11:10					70.07	I									52.20	DO
11:10-11:20					75.79	I									50.05	DO
11:20-11:30					106.54	I	100.10	I	72.22	I						
11:30-11:40					115.12	DO	100.82	I	61.49	I	52.20	DO			54.34	DO
11:40-11:50					105.11	DO					47.91	DO			51.48	DO
11:50-12:00			2.86	DR			199.49	I			52.91	I			59.35	DO
12:00-12:10			3.58	DO	148.72	I	103.68	DO	62.92	DO					75.08	OF
12:10-12:20			3.58	DO	114.40	DO	77.22	I	42.90	DO	129.42	I	47.91	DO	50.05	I
12:20-12:30			4.29	DO	87.95	DO	64.35	I	42.90	DO	94.38	I			50.05	I
12:30-12:40			64.35	I	78.65	DO	61.49	DO	71.50	DO					51.48	I

	21 August 2016		22 August 2016		23 August 2016		24 August 2016		25 August 2016		26 August 2016		27 August 2016		28 August 201	
Average time	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**	**Averaged PM4 (µg/m³)**	**M-E**
12:40-12:50			4.29	DO	75.79	I	58.63	I	40.76	I	129.42	I	44.33	I	51.48	I
12:50-13:00			4.29	I	77.22	DO	62.92	I	178.04	DO	94.38	DO	47.19	I		
13:00-13:10			8.58	I	74.36	DO			35.75	DO					55.06	I
13:10-13:20			12.16	I	78.65	I			56.49	I	49.34	DO			52.91	I
13:20-13:30			12.16	I	84.37	I			72.22	I	69.36	I				
13:30-13:40			19.31	DO	96.53	I			61.49	I	60.78	I	50.05	DO		
13:40-13:50					101.53	I			48.62	I	61.49	I				
13:50-14:00			12.16	I	96.53	DO			45.05	DO	48.62	DO				
14:00-14:10			12.16	I	95.81	DO	178.04	DO	44.33	DO	50.77	DO	45.76	I		
14:10-14:20					102.25	I	35.75	DO	82.23	I	50.77	I				
14:20-14:30			7.15	DO	100.10	I	56.49	DO			45.76	DO				
14:30-14:40			2.86	I	100.82	I	72.22	DO	100.10	I	45.76	DO	62.92	I		
14:40-14:50					199.49	I	61.49	DO	97.24	I	42.90	DO	55.77	I		
14:50-15:00			77.22	I	103.68	I	48.62	DO	100.82	I	48.62	DO				
15:00-15:10					77.22	I	45.05	DR	75.79	DO	46.48	DO				
15:10-15:20			1.43	I	64.35	I	44.33	I	70.07	DO	48.62	DO				
15:20-15:30			2.15	I	61.49	O	82.23	I	56.49	DO	49.34	DO				
15:30-15:40					58.63	O			175.18	DO	69.36	I				
15:40-15:50			3.58	I	62.92	O			51.48	DO	60.78	I				
15:50-16:00			3.58	DO	699.99	O			40.76	DO						
16:00-16:10					62.92	O			41.47	DO						
16:10-16:20	27.17	DO	1.43	DO					47.19	DO						
16:20-16:30	27.17	DO	3.58	I					188.05	DO			59.35	DO		
16:30-16:40	40.76	DO			70.07	DO			171.60	DO			61.49	DO		
16:40-16:50	33.61	DO	20.02	I					135.85	DO	61.49	DR	117.98	I		
16:50-17:00	31.46	I	60.06	I	106.54	DO	64.35	IF	106.54	DO			587.02	I		
17:00-17:10	30.03	I														
17:10-17:20																
17:20-17:30																
17:30-17:40									289.58	DO						
18:00-18:10									2780.64	DO						

7.4 Annexure D – Integrated exposure concentration and integrated potential dose calculation

Table 7.2. Derivation of time-weighted, integrated exposure concentrations and potential doses for an individual carrying a SidePak and GPS monitor between 21 and 28 August 2013 (U.S. EPA, 2011)

21 August 2013							
Micro-environment	Average PM4 concentration (C µg/m^3)	Time fraction (t)*	C x t (µg/ m^3)	Microenvironment contribution (%)	Potential dose (µg/ day)	PD*t (µg/day)	PD*t (mg/day)
Inside a house (I)	189.64	0.33	63.21	73%	3276.98	1092.33	1.092326
Directly outside a house (DO)	35.21	0.67	23.47	27%	608.43	405.62	0.405619
On a dirt road (DR)	0.00	0.00	0.00	0%	0.00	0.00	0
On a tar road (TR)	0.00	0.00	0.00	0%	0.00	0.00	0
On an open field (OF)	0.00	0.00	0.00	0%	0.00	0.00	0
	Time-weighted exposure concentration		**86.69**		**Time-weighted dose**		**1.50**

22 August 2013							
Micro-environment	Average PM4 concentration (C ug/m^3)	Time fraction (t)*	C x t (ug/ m^3)	Microenvironment contribution (%)	Potential dose (µg/ day)	PD*t (µg/day)	PD*t (mg/day)
Inside a house (I)	259.37	0.59	152.04	91%	4481.91	2627.33	2.63
Directly outside a house (DO)	36.78	0.38	13.95	8%	635.56	241.07	0.24
On a dirt road (DR)	36.78	0.03	1.27	1%	635.56	21.92	0.02
On a tar road (TR)	0.00	0.00	0.00	0%	0.00	0.00	0.00
On an open field (OF)	0.00	0.00	0.00	0%	0.00	0.00	0.00
	Time-weighted exposure concentration		**167.26**		**Time-weighted dose**		**2.89**

23 August 2013							
Micro-environment	Average PM4 concentration C (ug/m^3)	Time fraction (t)*	C x t (ug/ m^3)	Microenvironment contribution (%)	Potential dose (µg/ day)	PD*t (µg/day)	PD*t (mg/day)
Inside a house (I)	207.70	0.49	101.43	84%	3589.06	1752.79	1.75
Directly outside a house (DO)	39.14	0.47	18.20	15%	676.34	314.58	0.31
On a dirt road (DR)	39.14	0.02	0.91	1%	676.34	15.73	0.02
On a tar road (TR)	39.14	0.02	0.91	1%	676.34	15.73	0.02
On an open field (OF)	0.00	0.00	0.00	0%	0.00	0.00	0.00
	Time-weighted exposure concentration		121.46		**Time-weighted dose**		2.10

24 August 2013							
Microenvironment	Average PM4 concentration (C ug/m^3)	Time fraction (t)*	C x t (ug/ m^3)	Microenvironment contribution (%)	Potential dose (µg/ day)	PD*t (µg/day)	PD*t (mg/day)
Inside a house (I)	147.80	0.43	63.34	73%	2553.98	1094.56	1.094565
Directly outside a house (DO)	40.07	0.48	19.08	22%	692.41	329.72	0.329719
On a dirt road (DR)	40.07	0.05	1.91	2%	692.41	32.97	0.032972
On a tar road (TR)	0.00	0.00	0.00	0%	0.00	0.00	0
On an open field (OF)	40.07	0.05	1.91	2%	692.41	32.97	0.032972
	Time-weighted exposure concentration		86.24		**Time-weighted dose**		1.49

25 August 2013							
Microenvironment	Average PM4 concentration (C ug/m^3)	Time fraction (t)*	C x t (ug/m^3)	Microenvironment contribution (%)	Potential dose (µg/day)	PD*t (µg/day)	PD*t (mg/day)
Inside a house (I)	237.24	0.37	88.12	77%	4099.51	1522.67	1.522674
Directly outside a house (DO)	42.06	0.63	26.44	23%	726.80	456.84	0.456844
On a dirt road (DR)	0.00	0.00	0.00	0%	0.00	0.00	0
On a tar road (TR)	0.00	0.00	0.00	0%	0.00	0.00	0
On an open field (OF)	0.00	0.00	0.00	0%	0.00	0.00	0
	Time-weighted exposure concentration		114.56		**Time-weighted dose**		1.98

26 August 2013							
Microenvironment	Average PM4 concentration (C ug/m^3)	Time fraction (t)*	C x t (ug/m^3)	Microenvironment contribution (%)	Potential dose (µg/day)	PD*t (µg/day)	PD*t (mg/day)
Inside a house (I)	86.82	0.38	33.39	62%	1500.25	577.02	0.58
Directly outside a house (DO)	32.67	0.58	18.85	35%	564.54	325.69	0.33
On a dirt road (DR)	32.67	0.04	1.26	2%	564.54	21.71	0.02
On a tar road (TR)	0.00	0.00	0.00	0%	0.00	0.00	0.00
On an open field (OF)	0.00	0.00	0.00	0%	0.00	0.00	0.00
	Time-weighted exposure concentration		53.50		**Time-weighted dose**		0.92

27 August 2013							
Microenvironment	Average PM4 concentration (C ug/m^3)	Time fraction (t)*	C x t (ug/m^3)	Microenvironment contribution (%)	Potential dose (µg/ day)	PD*t (µg/ day)	PD*t (mg/day)
Inside a house (I)	124.62	0.44	54.52	73%	2153.43	942.13	0.94
Directly outside a house (DO)	36.50	0.56	20.53	27%	630.72	354.78	0.35
On a dirt road (DR)	0.00	0.00	0.00	0%	0.00	0.00	0.00
On a tar road (TR)	0.00	0.00	0.00	0%	0.00	0.00	0.00
On an open field (OF)	0.00	0.00	0.00	0%	0.00	0.00	0.00
	Time-weighted exposure concentration		75.05		**Time-weighted dose**		1.30

28 August 2013							
Microenvironment	Average PM4 concentration (C ug/m^3)	Time fraction (t)*	C x t (ug/ m^3)	Microenvironment contribution (%)	Potential dose (µg/ day)	PD*t (µg/day)	PD*t (mg/day)
Inside a house (I)	272.10	0.52	142.53	83%	4701.9	2462.9	2.462894
Directly outside a house (DO)	60.57	0.43	25.96	15%	1046.6	448.6	0.448564
On a dirt road (DR)	0.00	0.00	0.00	0%	0.0	0.0	0
On a tar road (TR)	0.00	0.00	0.00	0%	0.0	0.0	0
On an open field (OF)	60.57	0.05	2.88	2%	1046.6	49.8	0.049844
	Time-weighted exposure concentration		171.37		**Time-weighted dose**		2.96

Notes:

Time fraction = Fraction of time spent in each environment

Micro-environment contribution = Percentage that each microenvironment contributes to the total time, time-weighted, integrated exposure (Ej)

Time-weighted integrated exposure (E) (µg/m³) = ∑ C x t

Potential dose (PD) = C x IR

Time-weighted integrated potential dose E (µg/m³) = ∑ C x t

Inhalation rate = 17.28 m^3/day

(U.S.EPA, 2011)

7.5 Annexure E – Daily average timeseries (after QA/QC)

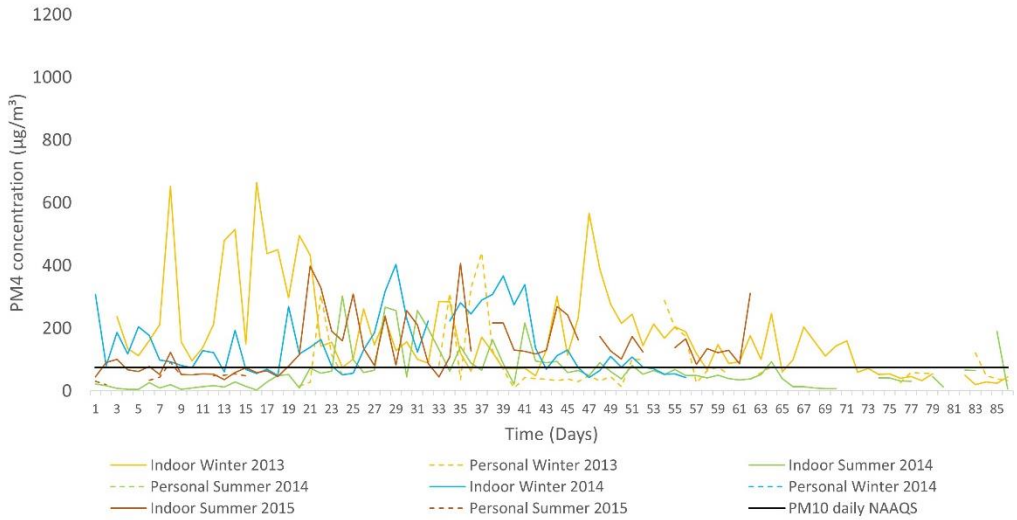

Figure 7.16 Timeseries of daily average PM concentrations (µg/m^3) in KwaDela across the campaigns

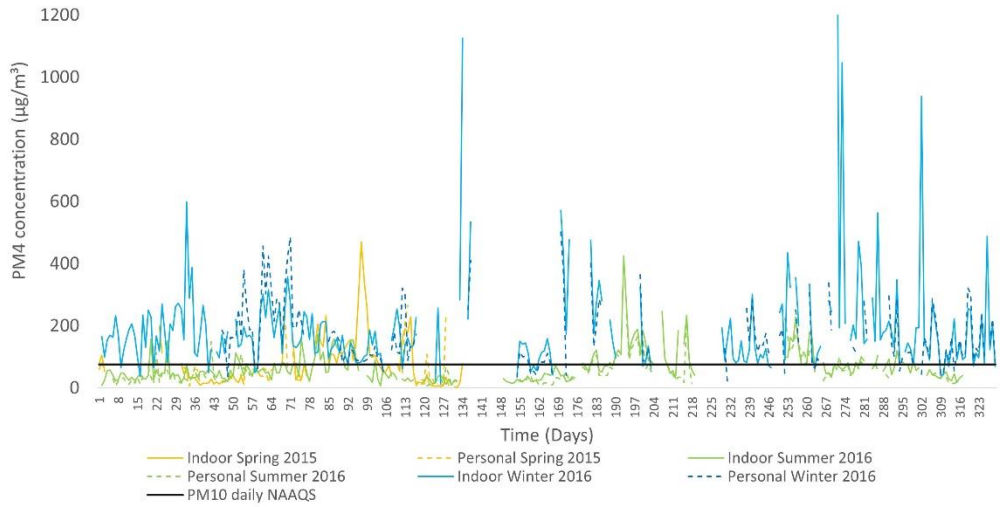

Figure 7.17 Timeseries of daily average PM concentrations (µg/m3) in KwaZamokuhle across the campaigns

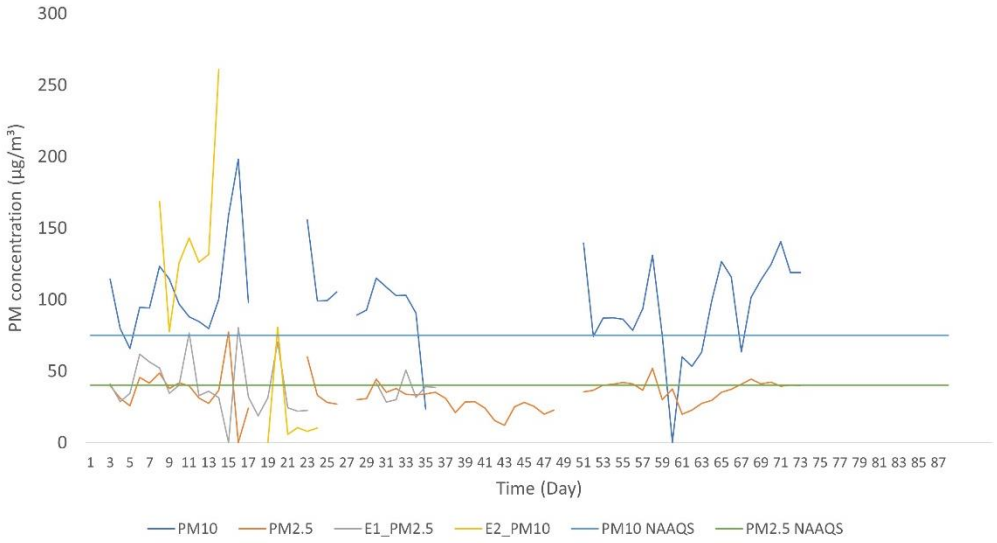

Figure 7.18 Timeseries of ambient daily average PM concentrations (µg/m^3) in KwaDela in winter 2013

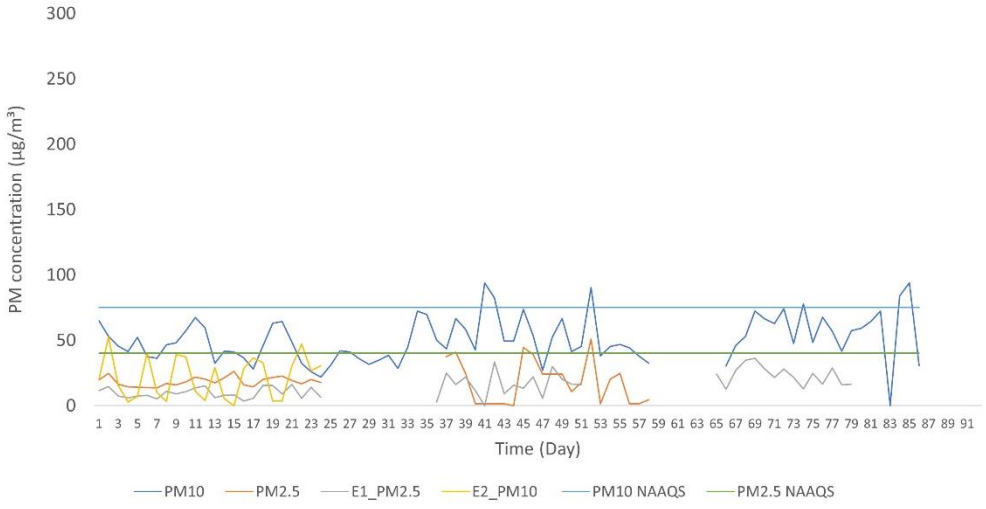

Figure 7.19 Timeseries of ambient daily average PM concentrations (µg/m^3) in KwaDela in summer 2014

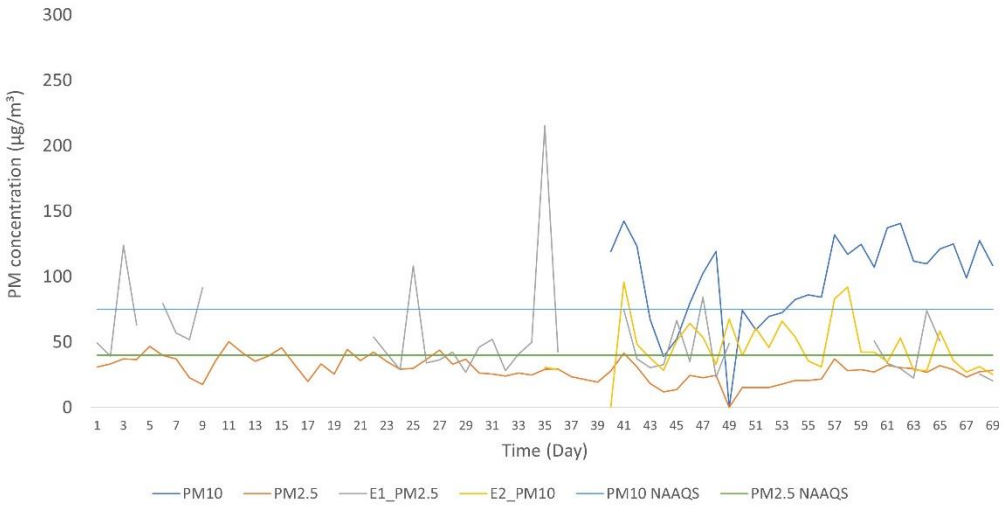

Figure 7.20 Timeseries of ambient daily average PM concentrations (µg/m^3) in KwaDela in winter 2014

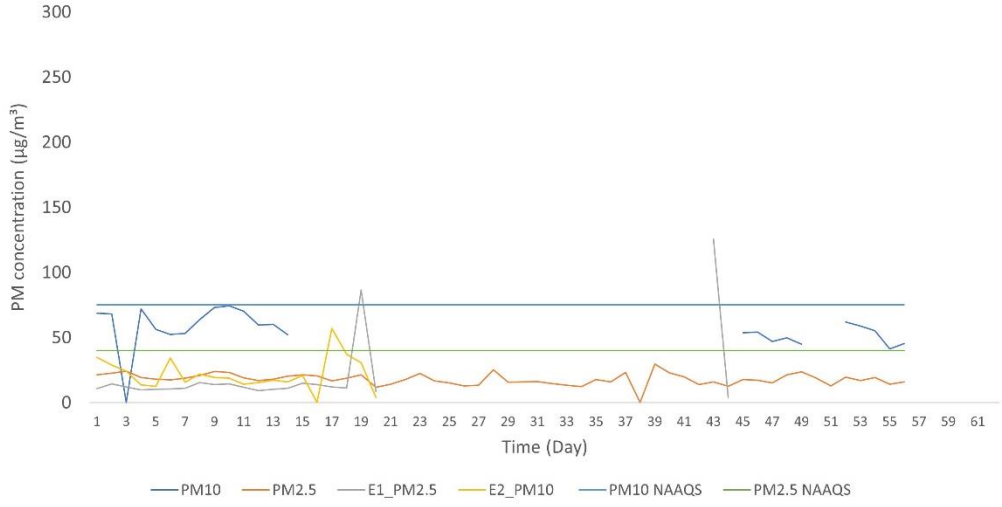

Figure 7.21 Timeseries of ambient daily average PM concentrations (µg/m^3) in KwaDela in summer 2015

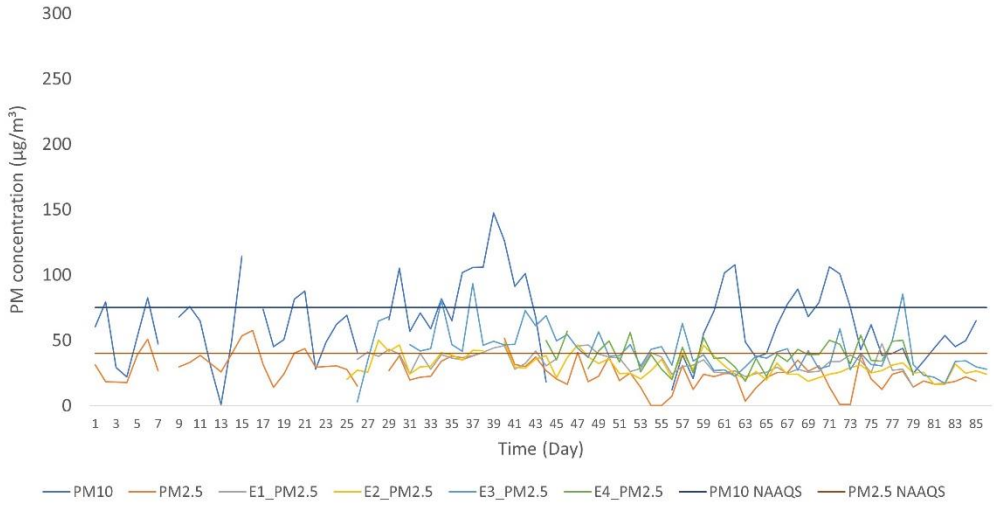

Figure 7.22 Timeseries of ambient daily average PM concentrations (µg/m^3) in KwaZamokuhle in spring 2015

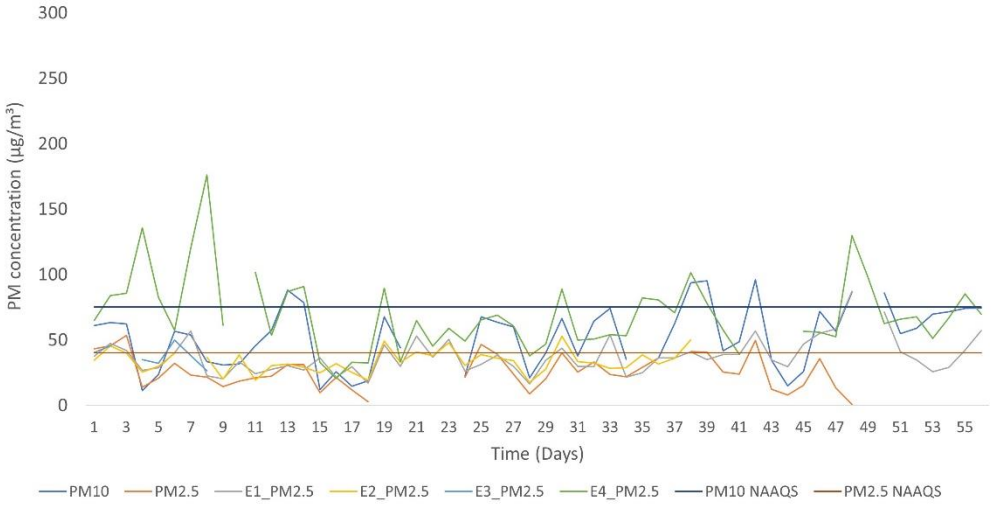

Figure 7.23 Timeseries of ambient daily average PM concentrations (µg/m^3) in KwaZamokuhle in summer 2016

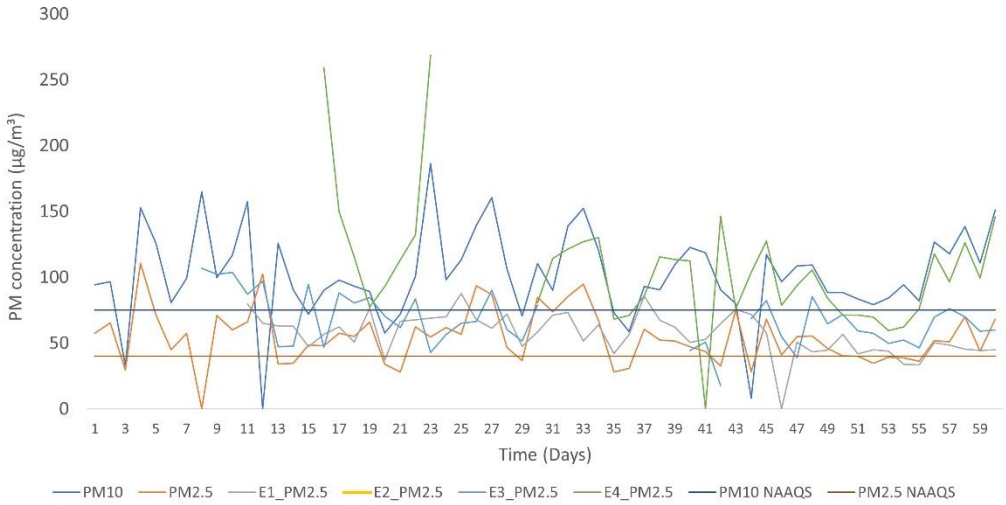

Figure 7.24 Timeseries of ambient daily average PM concentrations (µg/m^3) in KwaZamokuhle in winter 2016