



**DEVELOPMENT OF AN AIR QUALITY EARLY WARNING
SYSTEM FOR THE ETHEKWINI AND MSUNDUZI
MUNICIPALITIES**

By

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PREFACE

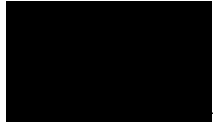
The research contained in this dissertation was completed by the candidate while based in the Discipline of Agrometeorology, School of Agriculture, Earth and Environmental Science of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, Sout Africa. The research was financially supported by Durban Research Action Partnership (DRAP).

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.



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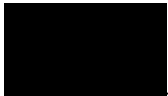
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ABSTRACT

The aim of this study was to assess the source and concentration of criteria air pollutants, as conditioned by the weather and climate conditions, in the eThekweni and Msunduzi Local Municipalities, in the KwaZulu-Natal Province. The outcomes of this assessment will contribute towards the establishment of an appropriate early warning system for the two municipalities, in order to reduce the risk of exposure to air pollution and to avoid the associated health risks. For this purpose, the study adopted various methods and tools to determine the status of air pollution within the municipalities, in terms of the exceedance of particles with an aerodynamic of less, or equal to, 2.5 micrometres (PM_{2.5}) and less than 10 micrometres (PM₁₀) of sulphur dioxide (SO₂), ozone (O₃) and nitrogen dioxide (NO₂). The National Ambient Air Quality Standards (NAAQS) and World Health Organisation (WHO) guidelines were used as a threshold for determining these exceedances. In addition, GIS software was used to determine the spatial distribution of the air pollutants, while the IBM SPSS Statistics Version 27 was used to determine the Pearson correlation between the meteorological parameters and the air pollutant concentration levels within the municipalities. The Openair package in R-Studio was used to determine the wind direction and wind speed within the areas, while the US EPA method was adopted to determine the Air Quality Index (AQI). The results of the exceedance study indicated that most of the air pollutants that were emitted exceeded those of the WHO and NAAQS thresholds, especially PM_{2.5} and PM₁₀, mostly during the winter period, when temperature inversion is at its strongest. A positive relationship was determined between the air pollutants and meteorological conditions. It is worth noting that the meteorological conditions were not the only factors influencing the concentration levels, but the emissions from industries and vehicles, the burning of fossil fuels for domestic purposes and landfill sites were also observed to be contributing factors to the air pollutant concentration within the municipalities. The results of the proposed AQI showed that most of the people living in eThekweni, especially those living south of Durban, were exposed during winter season to high concentrations of PM₁₀, PM_{2.5} and SO₂, while those of the proposed AQI in the Msunduzi Municipality were, in most cases, observed to be moderate throughout the seasons. In two cases, the Pietermaritzburg CBD and at the Pietermaritzburg Airport, the AQI was recorded as hazardous during spring and summer, respectively. According to the proposed AQI, the most dominant air pollutants are NO₂ and SO₂. The findings of the study suggest that people living in eThekweni and Msunduzi communities may breathe air harmful to their health and well-being, especially those living near industries and national highways. The overall findings of the study showed that the constitutional right of those living within these municipalities, “to live in an environment that is not

harmful to their health and wellbeing”, is being violated, since they are being exposed to high air pollutant concentrations.

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ABBREVIATIONS

AQMP	Air Quality Management Plan
AQI	Air Quality Index
CO	Carbon monoxide
DEA	Department of Environmental Affairs
EPA	Environmental Protection Agency
eTheAQI	EThekwini Air Quality Index
GIS	Geographical Information System
MsuAQI	Msunduzi Air Quality Index
NAAQS	National Ambient Air Quality Standard
NEMA	National Environment Management Act
NEMAQA	National Environmental Management: Air Quality Act
NO ₂	Nitrogen dioxide
O ₃	Ozone
PM	Particulate Matter
PM ₁₀	Particulate matter of fraction size of <10 micro meter diameter
PM _{2.5}	Particulate matter of fraction size of <2.5 micro meter diameter
PMB	Pietermaritzburg
PPB	Parts per billion
PPM	Parts per million
µg/m ³	Micrograms per cubic meter
RH	Relative Humidity
SAAQIS	South African Air Quality Information System
SAWS	South African Weather Service
SO ₂	Sulphur dioxide
SPSS	Statistical Package for the Social Sciences
Temp	Temperature

USEPA	United State Environmental Protection Agency
WD	Wind Direction
WHO	World Health Organisation
WS	Wind Speed

CHAPTER ONE

INTRODUCTION

1.1 Background

Air is essential for human survival; therefore, the introduction of harmful chemicals into the atmosphere causes air pollution. Air pollution is recognized today as the greatest environmental threat to human health (WHO, 2021). Exposure to air pollution in humans varies from mild effects, such as itching eyes and a runny nose, to worse scenarios, like death from chronic respiratory diseases, depending on the health status of an individual (Orellano et al., 2021; WHO, 2021; Buthelezi et al., 2019).

The Global Disease Burden study estimates that exposure to indoor and ambient air pollution causes about 5.5 million premature deaths (OECD, 2016). In 2016, air pollution-related deaths were approximately 7 million (WHO, 2018), and recent data have recorded approximately 9 million premature deaths annually, worldwide (WHO, 2021). This increase in deaths relating to air pollution emissions indicates that there is a need for urgent intervention.

In the underdeveloped and developing countries across Africa, a total of one-third of the population is faced with the double burden of indoor and ambient air pollution. For instance, the study by Fisher et al. (2021) found that air pollution accounts for 1.1 million premature deaths annually in Africa. These concerning deaths were also noted by Simwela et al. (2018), who discovered that rising air pollution concentrations in African nations had brought air pollution to a worrisome level.

Air pollutants that pose the above-mentioned health risks are particles (PM_{2.5} and PM₁₀), nitrogen oxides (NO_x), sulphur dioxide (SO₂), carbon dioxide (CO₂) and ozone (O₃), (HEI, 2017; Wright et al., 2017; WHO, 2016). These pollutants are largely related to the rapid increase in indoor air pollution due to exposure to household fuels used for domestic purposes (Jafta et al., 2019) and to air pollution caused by traffic, energy generation and industries, particularly in South Africa (Simwela et al., 2018). Furthermore, data from the WHO indicated that air pollution in 2016 was responsible for 22 917 premature deaths per year in South Africa (Climate Transparency Report, 2020).

In recent years, policy frameworks, such as the National Environmental Management Air Quality Act (NEMAQA) 39 of 2004, have been established in South Africa. These political instruments are aimed at reducing exposure to air pollution, maintaining air quality and ensuring that human health is not violated in the constitutional right to an environment. According to authors such as Tshela and Wright (2019), some of the strategic objectives of NEMAQA to minimise air pollution have unfortunately not yet been achieved. In this regard, some studies have found that people living near the sources of air pollution, especially those

susceptible groups, like young children, elderly and people suffering from prevailing illnesses, are susceptible to respiratory diseases (Njoku et al., 2019; Buthelezi et al., 2019; Olufemi et al., 2018).

Therefore, this study has determined that there are significant exceedances of air pollutants, which are classified as criteria pollutants, due to their significant impact on human health and their spatial distribution within municipalities. Furthermore, the relationship between weather conditions and air pollution have been analysed, in order to understand behaviour of air pollutants over four seasons (summer, autumn, winter and spring). In moreover, a combined Air Quality Index, that will use both WHO and NAAQS guidelines, was proposed to reduce health risks. These findings have important practical applications for municipalities because they: a) raise an awareness to the state of air quality to which the public is exposed, and b) they provide guidance on what should be done about it. It is against this background that the present study proposes a local Air Quality Index, which will be used as an early warning system to increase the awareness of exposure to high concentrations of harmful air pollutants in municipalities.

1.2 Motivation

The Bill of Rights, under Section 24 of the South African Constitution, “states that everyone has the right to: (a) an environment that is not harmful to their health or well-being; and to (b) an environment that is protected, for the benefit of present and future generations, through reasonable legislative and other measures, namely:

- to prevent pollution and ecological degradation;
- to promote conservation; and
- to secure ecologically-sustainable development and the use of natural resources, while promoting justifiable economic and social development” (South Africa, 1996).

Air pollution in South Africa has been linked to respiratory illnesses due to the expansion of fossil fuel-based industries that release air pollutants into the environment. Policies and regulations have subsequently been implemented to guarantee that the right to a clean environment is fulfilled. These policies and regulations provide reasonable measures: a) to prevent pollution and ecological degradation, and b) to ensure ecologically-sustainable development, while promoting justifiable economic and social development.

In 2004, National Environmental Management Air Quality Act No. 39 (NEMAQA) enacted special air quality measures and the introduction of national air quality standards and standards for the control, management and control of air quality in all sectors, and introduced national air quality standards and standards for the protection of the environment through the introduction of national air quality standards

and standards for the control, management and control of air quality in all sectors (South Africa, 2004). These regulations are more critical for South Africa, that has since been declared to be one of the most polluted regions on earth by the Greenpeace 2018 Report (Greenpeace, 2018). A study by Tshehla and Wright, (2019) studied the impact of the NEMAQA on reducing air pollution and they found that the Act is failing to assist in reducing air pollution emission due to failure to effectively reduce pollution from domestic burning, waste burning, biomass burning, vehicle emissions, and mining activities in air pollution hotspots make achieving the desired reduction impossible. To support these findings, a report by the World Health Organisation (WHO, 2016) found that air pollution in South Africa was responsible for 22 917 deaths per year (Climate Transparency Report, 2020).

In the KwaZulu-Natal province, air pollution is a notable problem, and therefore, public awareness of state of the air quality is very important for preventing air pollution, which causes respiratory diseases and premature deaths (Shezi and Wright, 2018; Gumede et al., 2017). A study by Naidoo et al. (2013) discovered that school pupils, especially south of Durban, were subjected to a high concentration of air pollutants, such as SO₂ and PM₁₀, and that respiratory diseases, such as asthma, were reported. Furthermore, research by Kistnasamy et al. (2008) and Mentz et al. (2017) reported evidence of coughing, shortness of breath and chest tightness in schoolchildren who are exposed to air pollution. The evidence of these studies proves that air pollution is a challenge in KZN province, and that more studies are needed to produce some much-needed solutions.

Therefore, local authorities must consider factors and drivers influencing the implementation of housing and economic development policies in terms of environmental and human health protection (Tshehla and Wright, 2019). For example, people in the eThekweni and Msunduzi Municipalities live in areas where the air quality exceeds the National Ambient Air Quality Standard (NAAQS), particularly south of Durban and in Pietermaritzburg. According to Naidoo et al. (2013) and Mentz et al. (2017) exposure unhealthy air in the south of Durban exacerbated, or triggered, respiratory diseases among schoolchildren. Furthermore, Khumalo (2019) showed that adults and children near the Pietermaritzburg landfill are exposed to harmful substances that threaten their health. Therefore, instruments such as the local Air Quality Index will assist municipalities to ensure minimum exposure to harmful air pollutants by the public, as they enforce stricter policies and seek to identify the air pollution emitters.

1.3 Research Aim

The study aims to assess sources of air pollutants and concentration of criteria air pollutants that are conditioned by the weather and climatic conditions. The overarching aim is to propose an appropriate air quality early warning system eThekweni Municipality (primary site) and Msunduzi Local Municipality (secondary site) in the KwaZulu-Natal Province.

1.4 Specific Objectives

The specific objectives of this study are:

- 1.4.1 to determine the air pollution exceedances and spatial distribution of criteria air pollutants in eThekweni and Msunduzi Municipalities;
- 1.4.2 to determine the relationship between the meteorological factors and air pollution at the eThekweni and Msunduzi sites; and
- 1.4.3 to propose the most suitable Air Quality Index for the eThekweni and Msunduzi Municipalities, which is in line with both local and international practices, in order to limit the health risks.

1.5 Research Questions

The research questions that will be addressed in this thesis are as follows:

- 1.5.1 Which areas within the eThekweni Metropolitan and Msunduzi local municipalities have a high concentration of air pollutants?
- 1.5.2 Are the criteria pollutants found within eThekweni and Msunduzi study sites being emitted in the area?
- 1.5.3 Do meteorological factors influence the distribution of air pollution?

1.6 Summary of this Dissertation

This dissertation is divided into the following seven chapters:

Chapter One describes the context of air pollution worldwide, in South Africa and the municipalities of eThekweni and Msunduzi. The study describes in detail the importance of the research, the main objective, the aim, and the research question, and summarizes the research. **Chapter Two** provides a literature review of the impact of air pollution on the world and describes the fundamentals of each pollutant standard and its impact on human health. The literature provides literature on the relationship between atmospheric pollutants and weather parameters, the implementation of air quality standards for managing air pollution, and the introduction of an air quality index (AQI) to prevent human exposure to air pollutants. Finally, it deals with South Africa's air quality management and the tools used to prevent exposure to air pollutants. **Chapter Three** reviews the impact of air pollution on human health in the cities of eThekweni and Msunduzi. **Chapter Four** describes the study area, data sets from municipal air quality monitoring stations,

and materials and methods adopted in the study. **Chapter Five** provides the results and discussion sections, a graphical representation of the air pollution exceedances, as well as the GIS maps that were used to present the spatial distribution of air pollutants within the study area. Statistical Package for the Social Sciences (SPSS) was used to determine the relationship between the meteorological parameters and air pollutants, the R-package was used to present the wind speed and direction by using wind roses, and lastly, the air quality status was determined by using the proposed eThekweni and Msunduzi AQI (eThAQI and MsuAQI) and by using the WHO guidelines and the NAAQS as thresholds. **Chapter Six** provides the discussion, conclusions and recommendations for improving the management of air pollution and for the prevention of human exposure to harmful air pollutants. **Chapter Seven** provides the references.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Air pollution is defined as the introduction of chemicals or biological substances into the environment, causing damage or discomfort to humans and other organisms (Manisalidis et al., 2020; Ferrante et al., 2012; Hutton, 2011). Various factors, such as an increase in industrial activity, combustion, the transportation of household fuel and the failure to implement air quality policies, have been cited as the main drivers of the emission of air pollutants (WHO, 2016). Primary sources are pollutants released directly from sources, and secondary pollutants are pollutants that develop when primary pollutants react with themselves or with other surrounding influences such as the sun.

Air pollution is a global concern; therefore, understanding the air quality in a region, as well as the policies around it, are critical. This chapter therefore presents a review of the relevant literature around the world, and it will then focus on South Africa, KwaZulu-Natal, as well as on two (2) municipalities (the eThekweni and Msunduzi Municipalities). The literature covers various topics, such as the criteria air pollutants in the country, the air quality, its health impacts, the tools that have been developed to prevent human exposure to air pollution, how the meteorological conditions influence the air quality and the development of an Air Quality Index, both internationally and locally.

2.2 The Fundamentals of Air Pollution

It is essential to understand the fundamentals of air pollution. Air pollutants can be emitted by natural processes such as volcanic activity, oceans and forests and by human activities such as emissions from fossil fuel combustion, transportation, and power plants. Air pollutants can be categorised as primary or secondary pollutants. Primary pollutants are substances that are directly produced by processes such as the combustion of fossil fuels from engine exhaust (Bhargave et al., 2020). Primary pollutants such as PM₁₀, PM_{2.5}, NO₂ and SO₂ can be converted by solar radiation and heat into secondary pollutants such as ozone (O₃) and other photochemical pollutants (Bhargave et al., 2020). Figure 2.1 shows the classification of air pollutants.

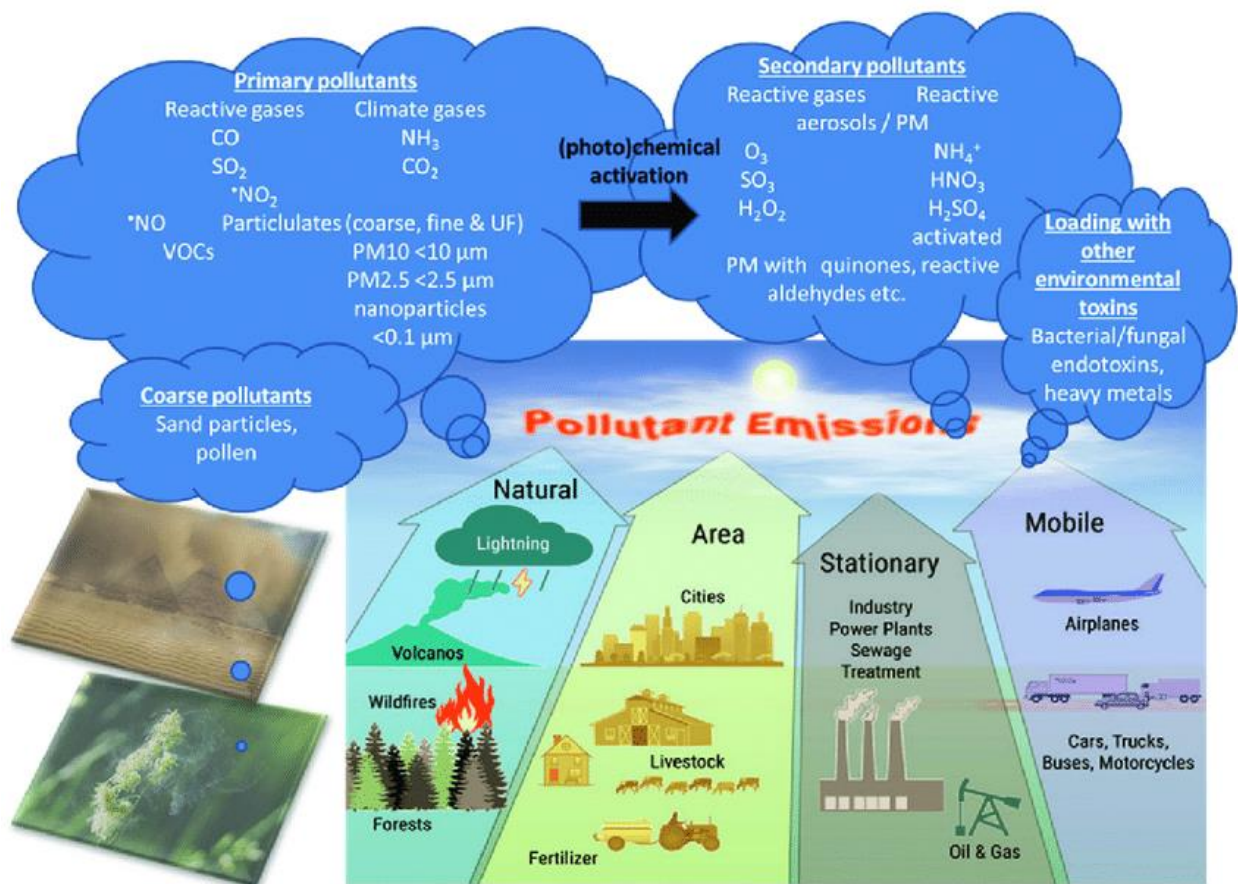


Figure 2.1 Primary and secondary air pollutant formation (Source: Hahad et al., 2020)

2.2.1 Particulate matter (PM₁₀ and PM_{2.5})

Particulate matter is defined as a mixture of solid and liquid particles in the air that have different chemical and physical properties (Hahad et al., 2020). The PM₁₀ particles are those that are 10 microns (μm) in aerodynamic diameter and smaller. The PM_{2.5} particles are 2.5 μm in aerodynamic diameter and smaller, and they can penetrate further into the respiratory system. Figure 2.2.2 shows a diagrammatic comparison of the sizes of the particulate matter. The sources of particulate matter range from motor vehicle engines, industrial processes, wood burning and natural causes, such as volcanic explosions (Vincent, 2019).

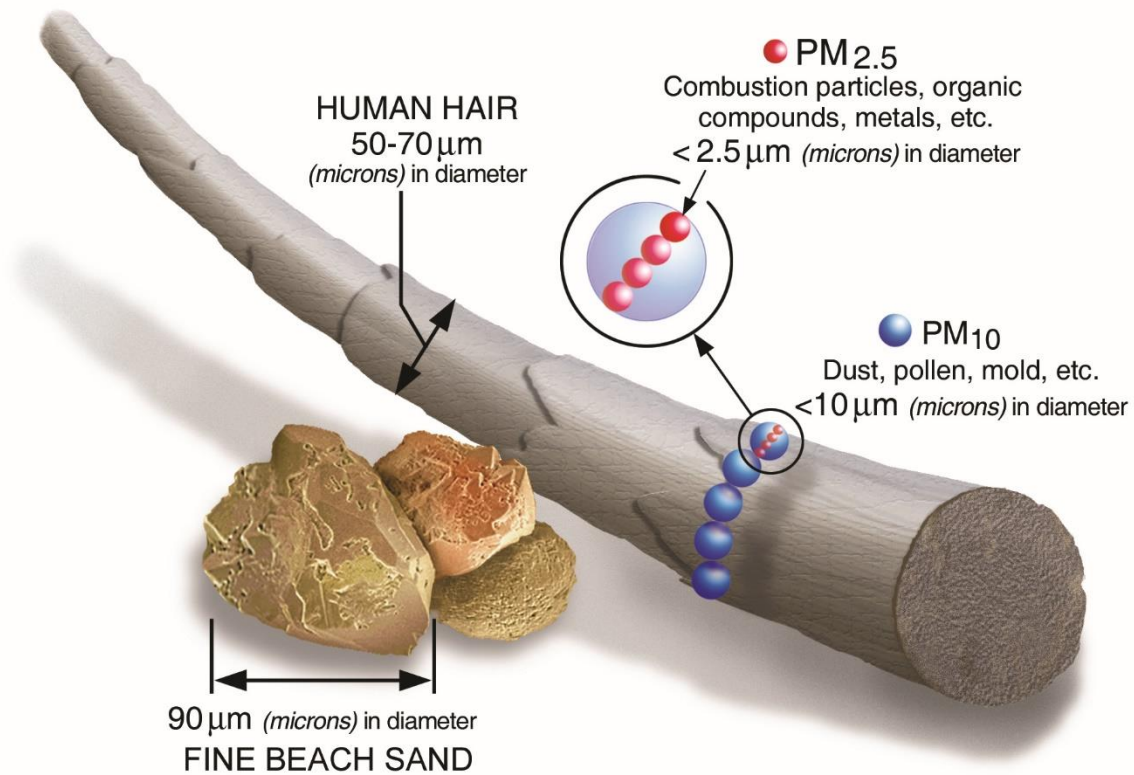


Figure 2.2 Size comparison of particulate matter (Source: <https://www.epa.gov/pm-pollution/particulate-matter-pm-basics>)

2.2.1.1 Health impacts of PM_{2.5} and PM₁₀

Exposure to such life-threatening pollutants can result in health risks, such as acute lower respiratory conditions in children under five years of age, Chronic Obstructive Pulmonary Disease (COPD), Ischaemic Heart Disease (IHD), as well as strokes and lung cancer in adults (WHO, 2016). Some sources, such as wood and other biomass fuels, are emitters of such fine particulate matter (WHO, 2018c). Figure 2.3 shows the depth of penetration according to their size; PM_{2.5} has been found to penetrate deep into the lungs and then it moves to the alveoli in the lungs. It is associated with diseases in the lower respiratory tract system. On the other hand, coarse particulate matter, such as PM₁₀, generally affects the respiratory tract system (Vincent, 2019; UNICEF, 2019).

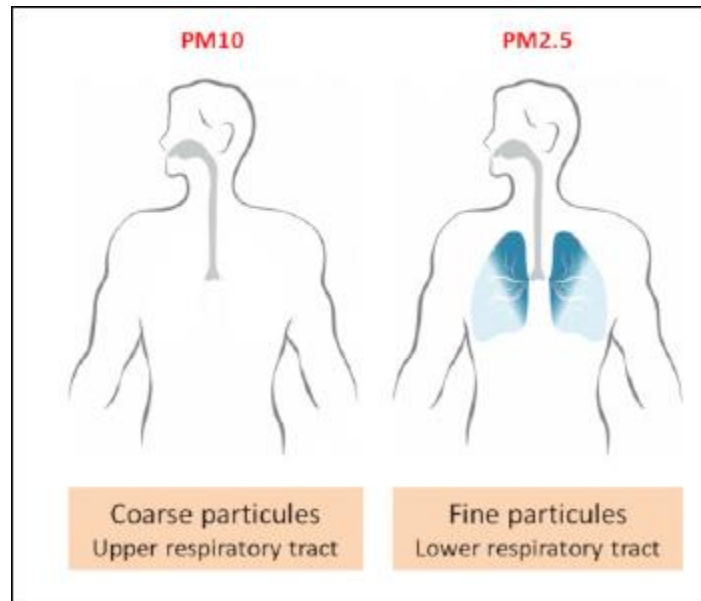


Figure 2.3 Lung penetration of PM₁₀ and PM_{2.5} (Source: Vincent, 2019)

2.2.2 Nitrogen dioxide (NO₂)

NO₂ can be described as odorous, brown and highly-corrosive. NO₂ sources include automobiles, wood burning, industrial processes, including electricity generation, the use of industrial boilers and diesel generators, and oil refining (Thabethe et al., 2021).

2.2.2.1 Health impacts of NO₂

It was reported that exposure to NO₂ had several negative effects on human health. This has been supported by a study by Han et al. (2017) who experimented on rats, with some rats being exposed to 0 mg/m³ of NO₂, while some were exposed to 2 mg/m³, and the last group was exposed to 5 mg/m³ of NO₂ for 27 days. The result of the experiment is illustrated in Figure 2.4 below; It shows that exposure to NO₂ leads to pulmonary inflammation, demonstrated by an increase in damage to epithelial cells of the lungs, infiltration of inflammatory cells and visible mucous secretion, and compares them with control groups of rats that were not exposed to NO₂ (0 mg/m³). The study concluded that exposure to NO₂ can cause allergic airway inflammation and increase human sensitivity to exposure to NO₂.

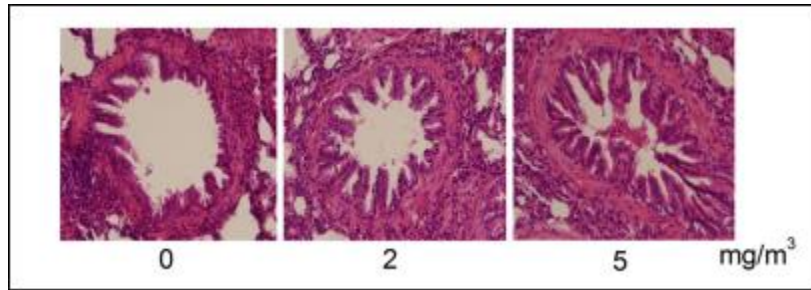


Figure 2.4 Effects of NO₂ exposure on lung histological change (Source: Han et al., 2017)

2.2.3 Sulphur Dioxide (SO₂)

Sulphur dioxide is described as a colourless gas with a foul smell reminiscent of burning matches. The chemical formula of this pollution is SO₂, ranging from natural volcanic activity to human-induced activities such as copper extraction, marine vessels, melting, petroleum refining, diesel engines, and burning fossil fuels contaminated with sulphur compounds (Orellano et al., 2021).

2.2.3.1 Health impacts of SO₂

Epidemiological studies have found that exposure to SO₂ has been linked to various health impacts. According to Badenhorst (2007), exposure to SO₂ may include eye, nose, throat, rhino (discharge of thin mucous membranes), edema, cough and reflex bronchoconstriction. In some instances, it can even lead to death, especially for those who live with pre-existing health issues (Orellano et al., 2021).

2.2.4 Ozone (O₃)

Ozone can be described as a very reactive gas; it is a secondary pollutant, since it is formed from a reaction between primary pollutants (pollutants that are formed directly from natural activities, as well as man-made activities, that lead to the emission of air pollutants, like VOCs and NO_x) in the presence of a third-body molecule that is able to absorb solar radiation (Zhang et al., 2019). Ozone is classified as a greenhouse gas; hence, an increase in ozone results in an increase in global warming, and vice versa, since ozone formation favours warm conditions. Figure 2.5 shows the formation of ozone.

Formation of Ground-Level Ozone

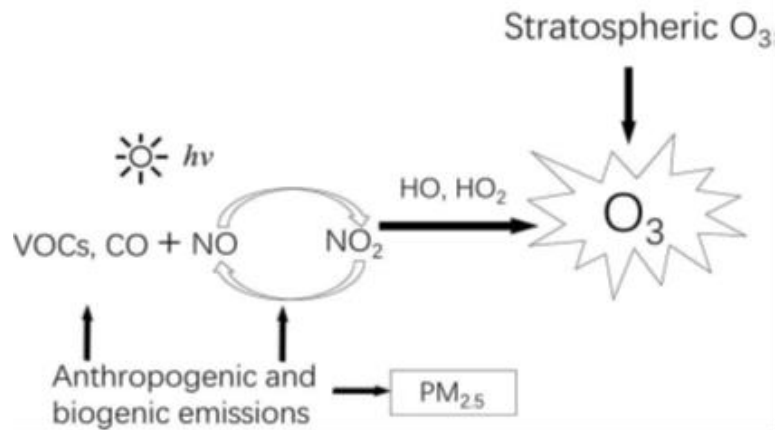


Figure 2.5 Ozone formation from UV reacting with VOCs, CO, NO_x. PM_{2.5} HO, HO₂
(Source: Zhang et al., 2019)

2.2.4.1 Health impacts of O₃

Excess ozone in the air can have a marked effect on human health and on the environment. Various scholars have reported that increased levels of O₃ can damage plants, resulting to reduced harvest of agricultural crops and reduced forest growth. For humans, it can cause breathing problems (shortness of breath and pain when taking a deep breath), it can trigger asthma (Cohen et al., 2017), reduce lung function (Nuvolone et al., 2018), and it can cause numerous lung diseases (WHO, 2018c). The human reaction to exposure differs, depending on a person's age, health status and body weight. Children whose respiratory system is underdeveloped are considered to be at risk from exposure to O₃ because, it increases the risk of respiratory diseases. Individuals living with existing illnesses are also considered to be at risk, since their immune system is already compromised by their existing disease, for example, asthma. The weight of an individual can be unhealthy and can increase the risk of exposure to any harmful air pollutants, such as O₃. A review study by Koman and Mancuso (2017) supported this; they found that overweight/obesity also increases health risks, when exposed to O₃ (see Figure 2.6).

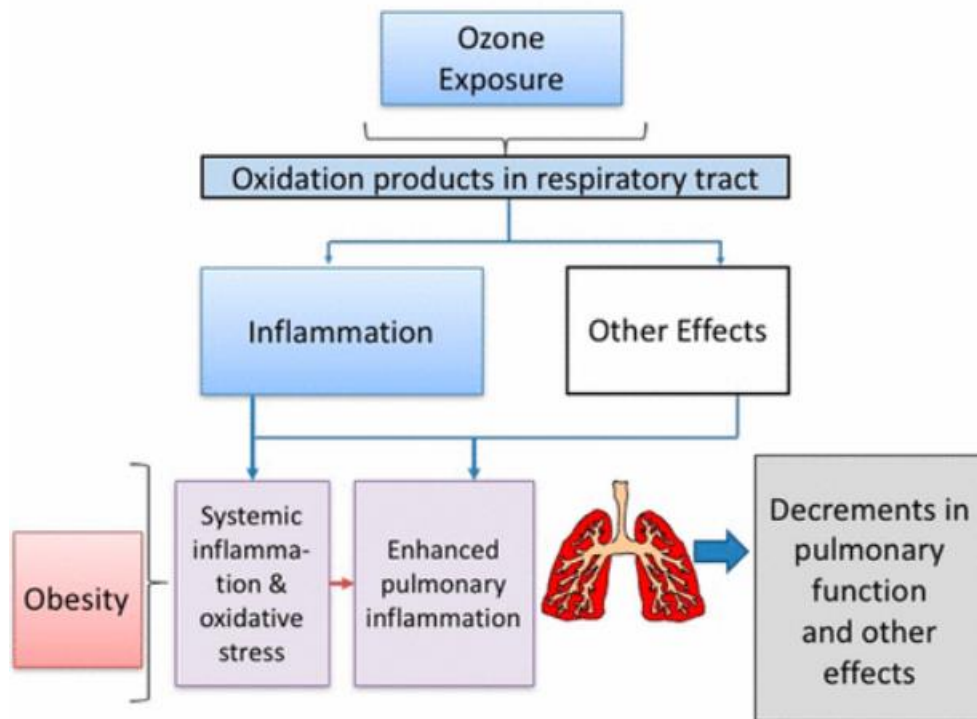


Figure 2.6 Health impacts from exposure to O₃ (Source: Koman and Mancuso, 2017)

2.3 Air Pollutants and Meteorological Factors

It is important to understand the impact of the environment on these criteria pollutants. Meteorological conditions affects the formation and transportation of air pollutants, as well as the changes in the pollutant concentration levels (Liu et al., 2020). Wind speed and direction factors, for example, are responsible for the dispersion and directing of air pollutants such as PM₁₀, PM_{2.5}, SO₂, O₃, NO₂ and CO. The wind transports air pollutants from the source of their emission to areas far from their source of origin (Cui et al., 2018; Jury, 2017; Perez et al., 2020). Furthermore, an increase in the wind speed results in the dilution of air pollutants. A study in Poland found that an increase in wind speed results in a significant decline in the concentration of air pollution (Radzka, 2019). Figure 2.7 shows the recirculation of air pollutants along the east coast of South Africa.

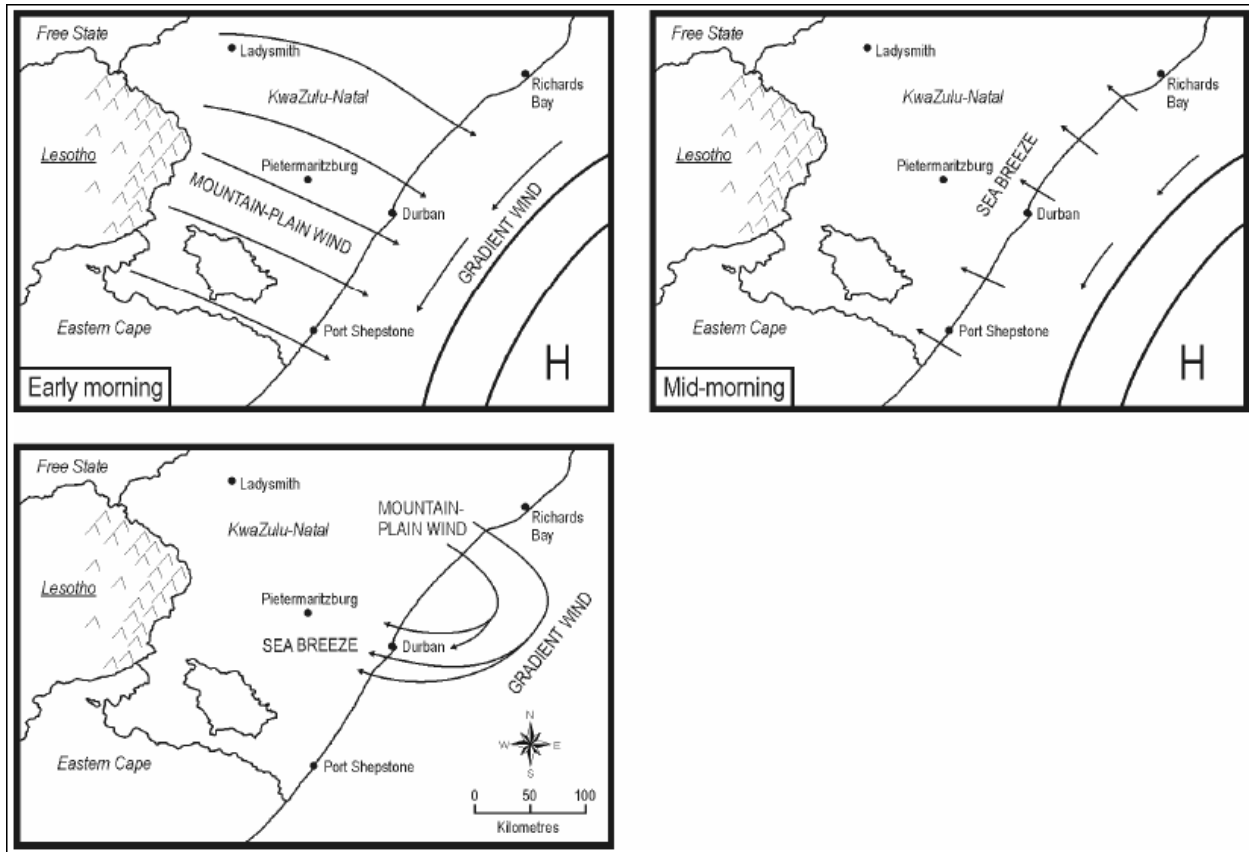


Figure 2.7 Re-circulation of pollutants along the east coast of South Africa (Source: Tyson and Preston-Whyte, 2000)

Temperature affects the movement of air pollutants, and heat from the sun leads to an increase in the surface temperature of the earth. This increase in the temperature of the surface of the Earth, especially during the day, improves the convection of mixtures and promotes the dispersion of pollutants. Some processes, such as chemical reactions, gas-particle conversion and motor vehicle emissions, are also temperature-dependent (Jacob and Winner, 2009; Zhang et al., 2019). In addition, photochemical reactions, especially O_3 , have been found to increase with high temperatures (Doherty et al., 2009). The relative humidity affects the natural deposition process of some pollutants; this means that moisture particles adhere to some pollutants, which then results in an accumulation of the atmospheric pollutant concentration (Jacob and Winner, 2009; Hernandez et al., 2017).

2.4 Air Quality Management

Since air pollution has no borders, due to the transportation of air pollution by the wind (Tyson and Preston-Whyte, 2000), it is therefore important to manage air pollution from its source point. The World Health Organisation has developed air quality guidelines for all countries to implement, although many countries are still not complying with them (WHO, 2022). Some countries have developed locally-based National Ambient Air Quality Standards (NAAQS). These standards are used by countries as a threshold to indicate whether air pollution is improving or deteriorating (EPA, 2013). Some air pollutants pose a risk to the environment and human health, even at their lowest concentration (Manisalidis et al., 2020). For example, Australia has developed its own NAAQS, which is called the Ambient Air Quality National Environment Protection Measure (AAQ NEPM), to reduce air pollution. It has developed standards for seven (7) pollutants, namely, carbon monoxide (CO), nitrogen dioxide (NO₂), sulphur dioxide (SO₂), lead (Ld), ozone (O₃) and particulate matter (PM_{2.5} and PM₁₀). The air quality in Australian cities has improved greatly over the years, due to the thresholds of these pollutants (Paton-Walsh et al., 2019) (refer to Table 2.1 for the air pollutant standards of Australia)

Table 2.1 Standards of pollutants in Australia (Source: modified from Paton-Walsh et al., 2019)

Column 1 Item	Column 2 Pollutant	Column 3 Average period	Column 4 Maximum concentration standard	Column 5 Maximum allowable exceedances
1	Carbon monoxide	8 hours	9.0 ppm	1 day a year
2	Nitrogen dioxide	1 hour 1 year	0.12 ppm 0.03 ppm	1 day a year None
3	Photochemical oxidants (such as Ozone)	1 hour 4 hours	0.10 ppm 0.08 ppm	1 day a year 1 day a year
4	Sulphur dioxide	1 hour 1 day 1 year	0.20 ppm 0.08 ppm 0.02 ppm	1 day a year 1 day a year None
5	Lead	1 year	0.5 µg/m ³	None
6	Particles as PM ₁₀	1 day 1 year	50 µg/m ³ 25 µg/m ³	None None
7	Particles as PM _{2.5}	1 day 1 year	25 µg/m ³ 8 µg/m ³	None None

The United States Environmental Protective Agency (US EPA) has established a NAAQS to improve its air quality. The standards were developed by EPA in 1971 and the air quality in the US has improved greatly since then. The EPA NAAQS has developed thresholds for six (6) air pollutants, namely, carbon monoxide (CO), nitrogen dioxide (NO₂), sulphur dioxide (SO₂), lead (Ld), ozone (O₃) and particulate matter (PM_{2.5} and PM₁₀). These pollutants were grouped as primary and secondary pollutants (refer to Table 2.2 below):

Table 2.2 USA air quality standards (source: <https://www.epa.gov/criteria-air-pollutants/naaqs-table>)

Pollutant [links to historical tables of NAAQS reviews]	Primary and Secondary	Averaging Time	Level	Form	
Carbon Monoxide (CO)	Primary	8 hours	9 ppm	Not to be exceeded more than once per year	
		1 hour	35 ppm		
Lead (Pb)	Primary and Secondary	Rolling 3 months average	0.15 µg/m ³	Not to be exceeded	
Nitrogen Dioxide (NO ₂)	Primary	1 hour	100 ppb	98 th percentile of 1-hour daily maximum concentrations, averaged over 3 years	
	Primary and Secondary	1 year	53 ppb	Annual Mean	
Ozone (O ₃)	Primary and Secondary	8 hours	0.070 ppm	Annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years	
Particulate Pollution (PM)	PM _{2.5}	Primary	1 year	12.0 µg/m ³	Annual mean, averaged over 3 years
		Secondary	1 year	15.0 µg/m ³	Annual mean, averaged over 3 years
		Primary and Secondary	24 hours	35 µg/m ³	98 th percentile, averaged over 3 years
	PM ₁₀	Primary and Secondary	24 hours	150 µg/m ³	Not to be exceeded more

Pollutant [links to historical tables of NAAQS reviews]	Primary and Secondary	Averaging Time	Level	Form
				than once per year on average over 3 years
Sulphur Dioxide (SO ₂)	Primary	1 hour	75 ppb	99 th percentile of 1-hour daily maximum concentration, averaged over 3 years
	Secondary	3 hours	0.5 ppm	Not to be exceeded more than once per year

NAAQS is a tool for developing air quality indicators (AQIs) to inform the public about the health status of the air they breathe. The AQI is a national uniform tool for reporting and forecasting the local air quality of the day; it is a health alarm tool. The way we live and breathe is impacted by local air quality, claim Cairncross et al. (2005). Like the weather, it can change day by day and time by time. Literature recognizes that health effects of air pollution are associated with an increase in the risk of respiratory symptoms, such as increased asthma attacks and reduced lung function, increased hospitalizations for respiratory and cardiovascular diseases, and increased mortality (Olanyian et al., 2018; Albers et al., 2015; Thabethe et al., 2014). The aim of the AQI is to help the public understand, at the individual level, what air quality around them means for their health, limit short-term exposure to air pollution and adjust their level of activity at increased levels of air pollution (Fraser et al., 2016; EPA, 2014; Chen and Copes, 2013). The AQI uses near-real-time monitored air quality data, it converts the data and reports them in the form of AQI categories, which helps the community to understand the status of air they breathe (COMEAP, 2011).

The AQI has been used internationally in the following countries: the United Kingdom (UK), the United States of America (USA), Belgium, France, Spain, Finland, Sweden, Canada, Mexico, Australia, New Zealand, Hong Kong, Singapore, Malaysia, Thailand, China, Macau, Indonesia and Taiwan (Cairncross et al., 2007).

The United Kingdom (UK) AQI

The UK has been using the AQI since 1990, and it was replaced in 1998 (Cairncross et al., 2007). In 2009, the AQI was reviewed again; it consisted of air pollutants such as SO₂, NO₂, CO and PM₁₀. After the review,

CO was removed, due to its low concentrations, and PM_{2.5} was added, due to its adverse health impacts on humans. The UK AQI is based on the short-term health effects of the stated air pollutants.

The current Air Quality Index developed by COMEAP is represented as a 10-point scale, with colour coding that makes it easy to read, as follows:

- Low: indicates a level of air pollution where it is unlikely that anyone will suffer from the negative effects of short-term exposure, including people with lung or heart disease who may be more vulnerable to the effects of air pollution;
- Moderate: represents the levels of air pollutants in which there may be few effects for sensitive people;
- high: associated with significant effects on vulnerable people; and
- Very high: indicates the level of air pollution, even healthy people can experience the adverse effects of short-term exposure.

The revised UK AQI takes into account the breaks for bands changes in ozone (O₃), nitrogen dioxide (NO₂) and particles (less than 10 m diameter, PM₁₀), and is more stringent than those for sulphur dioxide (SO₂). (COMEAP, 2011) (see Table 2.3 below).

Table 2.3 Boundaries between index points for each pollutant in the UK system (COMEAP, 2011)

Band	Index	Ozone	Nitrogen dioxide	Sulphur dioxide	PM _{2.5} particles	PM ₁₀ particles
		Running 8-hour mean (µg m ⁻³)	1-hour mean (µg m ⁻³)	15-minute mean (µg m ⁻³)	24-hour mean (µg m ⁻³)	24-hour mean (µg m ⁻³)
Low	1	0-26	0-66	0-88	0-11	0-16
	2	27-53	67-133	89-176	12-23	17-33
	3	54-80	134-200	177-265	24-35	34-50
Moderate	4	81-107	201-267	266-354	36-41	51-58
	5	108-134	268-334	355-442	42-46	59-66
	6	135-160	335-400	443-531	47-53	67-75
High	7	161-187	401-467	532-708	54-58	76-83
	8	188-213	468-534	709-886	59-64	84-91
	9	214-240	535-600	887-1063	65-70	92-100
Very High	10	241 or more	601 or more	1062 or more	71 or more	100 or more

The United States of America (USA)

The AQI was first introduced in the USA in 1976 and was called the Air Pollution Index (API) (US EPA, 1999). The US AQI includes five criteria pollutants, namely, ozone (O₃), particulate matter (PM), carbon monoxide (CO), sulphur dioxide (SO₂) and nitrogen dioxide (NO₂). The index scale is divided into general categories related to health messages (US EPA, 1999). The index is normalized by defining 100 as the index value of each pollutant in accordance with the National Air Quality Standard (NAAQS) and 500 as the index value of each pollutant. These index values serve to divide the index into categories, each category being identified by a simple informative descriptive identifier (Cairnross et al., 2007).

The US AQI values, descriptors and colours associated in their system are as follows:

- Good (0-50): indicates a positive message about the air quality;
- Moderate (51-100): indicates a message that the daily air quality is acceptable, from a public health perspective, but gives a warning to sensitive groups that, especially for O₃, it might result in potential chronic health effects;

- Unhealthy (101-150): indicates a health message for members of sensitive groups;
- Unhealthy (150-200): requires a health advisory of the more serious effects for sensitive groups and notice of the possible effects for the general population, when appropriate;
- Very unhealthy (201-300): indicates a health alert of the more-serious effects for sensitive groups and the general population; and
- Hazardous (301-500): indicates a health warning of emergency conditions.

Table 2.4 Breakpoints for the USA Air Quality Index (Cairncross, 2007; US EPA, 1999)

These breakpoints							Equal these AQIs	Categories
O ₃ (µm ⁻³) 8h	O ₃ (µgm ⁻³) 1h ^a	PM ₁₀ (µgm ⁻³) 24h	PM _{2.5} (µgm ⁻³) 24h	CO (mgm ⁻³) 8h	SO ₂ (µgm ⁻³) 24h	NO ₂ (µgm ⁻³) 24h		
0-28		0-54	0-5.4	0-5.1	0-90	b	0-0	Good
130-168		55-154	15.5-40	5.2-10.9	93-383	b	51-100	Moderate
170-208	250-328	155-254	41-65	11.0-14.4	386-596	b	101-150	Unhealthy for sensitive groups
210-248	330-408	255-354	66-150 ^c	14.5-17.9	599-809	b	151-200	Unhealthy
250-748	410-808	355-424	151-250 ^c	18.0-35.3	811-1607	124-237	201-300	Very unhealthy
d	10-1008	425-504	251-350 ^c	35.4-46.9	1609-2139	239-313	301-400	Hazardous
d	1010-1208	505-604	351-500	47.0-58.5	2141-2671	315-390	401-500	Hazardous

- (a) The AQI report may be based on 8-h O₃ values. In some cases, the value of the 1-h O₃ index may be calculated, and the maximum of the two is reported;
- (b) NO₂ has no short-term NAAQS and can only produce an AQI above 200;
- (c) If another SHL (significant harm level) for PM_{2.5} is published (in the United States), these figures will change accordingly; and
- (d) The eight-hour O₃ value does not define the highest AQI value (X301). AQI values of 301 or more are calculated with concentrations of 1-h O₃.

Finland

In Finland, Hämeikoski et al. (1998) developed an AQI based on the acute health effects and the long-term effects on nature and materials in the Helsinki metropolitan area. Finland AQI includes pollutants such as CO (1 hour and 8 hours), NO₂ (1 hour and 24 hours), SO₂ (1 hour and 24 hours), O₃ (1 hour) and PM₁₀ (24

hours).

The AQI value ranges from 10-150, with four bands:

- Good (<50): indicates no effects on humans and a slight effect on the ecosystem;
- Fair (51-100): indicates probable adverse reactions and effects on nature and materials;
- Passable (101-150): indicates possible harmful reaction on sensitive individuals and marked effects on vegetation and on materials; and
- Poor (>150): indicates the possible adverse effects on the sensitive sub-population and marked effects on nature and on materials.

Table 2.5 Comparison of AQI values with pollutant concentrations (Hämekoski et al., 1998)

Index	Co conc.		NO ₂ conc.		SO ₂ conc.		O ₃ conc.	PM ₁₀ (conc.)
	[mg/m ³ (ppm)]		[µg/m ³ (ppb)]		[µg/m ³ (ppb)]		[µg/m ³ (ppb)]	[µg/m ³ (ppb)]
	1h	8h	1h	8h	1h	8h	1h	24h
10	0.5(0.4)	0.5(0.4)	7 (3.4)	7 (3.4)	4 (1.4)	4 (1.4)	50 (23)	10
50	4(3.2)	4(3.2)	35 (17)	35 (17)	40 (14)	40 (14)	75 (35)	35
100	20(16)	8(6.4)	150 (73)	70 (34)	250 (88)	80 (28)	150 (70)	70
150	30(24)	12(10)	225 (110)	105 (51)	375 (131)	120 (42)	225 (105)	105

2.5 South African Air Quality Management

Since the Industrial Revolution, air pollution in South Africa has been a problem. To control air pollution, the 1965 Air Pollution Prevention Act No. 45 (APPA) was introduced with the aim of ensuring that:

- prevention of atmospheric pollution;
- the establishment of a National Advisory Committee on Air Pollution; and
- matters related thereto.

South Africa became a democratic country in 1994, and a new constitution of South Africa was introduced in 1996. The Bill of Rights in the South African Constitution under Section 24 (SA, 2009) states that everyone has the right “(a) to an environment that is not harmful to their health or well-being, and (b) to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that:

- prevent pollution and ecological degradation;
- promote conservation; and
- secure ecologically-sustainable development and the use of natural resources, while promoting justifiable economic and social development”.

Therefore, to ensure that the above-stated rights are not violated, the National Environmental Management Act 39 of 2004 (NEMAQA) was adopted, since the APPA did not adopt sufficient air quality standards and lacked a legal framework for the application of these measures (Held et al., 1996). Moreover, NEMAQA is committed to protecting the environment by taking reasonable measures to prevent pollution and degradation and ensure environmentally sustainable development while promoting just economic and social development. It also aims to establish national standards and standards regulating air quality monitoring, management and control in all spheres of government, both for specific air quality measures and for related issues (South Africa, 2004). NEMAQA includes declaration of priority areas in which areas that are considered to exceed the ambient air quality standards have the potential to exceed these standards. The priority areas in South Africa are the Vaal Triangle-Airshed Priority Area (VTAPA), the Highveld Priority Area (HPA) and the Waterberg-Bojanala Priority Area (WBPA). In addition, the Act requires the municipalities under paragraph 8(a) to monitor ambient air quality and emissions from point, non-point and mobile sources (South Africa, 2004), to ensure minimum exposure to harmful air pollutants by the public.

However, according to literature (DEA, 2015), the public of the eThekweni (south of Durban) and Msunduzi (Pietermaritzburg) Municipalities are still exposed to air pollutants that are harmful to their health and well-being. For instance, Mentz et al. (2019) found that people living south of Durban under the eThekweni Municipality reported respiratory symptoms, such as itchy noses and throats, burning and itchy eyes and itching skin, as a result of exposure to air pollution from industries, such as the petrochemical industry. In Pietermaritzburg, the New England Road landfill site is a significant threat to human health, due to fires within the landfill site during the winter season (Naidoo, 2009). It has been reported that communities living in areas close to air pollution sources, such as the landfill site, have at times been reliant on asthma pumps (Njoku et al., 2019). Therefore, these municipalities must review their policies and ensure that they are implemented, in order to minimise the emission of harmful pollutants.

Cairncross et al. (2007) developed an API for South Africa. The objective is to determine the relative risk of an established excess daily mortality rate associated with short-term exposure to common air pollutants (PM₁₀, PM_{2.5}, SO₂, O₃, NO₂, and CO). The API, consisting of a scale from 0 to 10, was used to evaluate air quality. The incremental risk values for each pollutants are assumed to be constant and the continuous exposure metric corresponding to the same relative risk corresponds to the same subindex value. Health risk warnings of the API is divided into four levels:

- Low (1-3): a low risk of increased death;
- Moderate (4-6): a moderate risk of increased death;
- High (7-9): a high risk of increased death; and
- Very High (10): a very high risk of increased death.

Table 2.6 Pollutant sub-indices for the DAAPS Air Pollution Index (API) system

Relative risk (RR)	Color	Sub-index value	Concentration corresponding to relative risk value						
			PM ₁₀ , 24-h average (µg/m ³)	PM _{2.5} , 24-h average (µg/m ³)	SO ₂ , 24-h average (µg/m ³)	O ₃ , 8 h maximum (µg/m ³)	O ₃ , 1-h Maximum (µg/m ³)	NO ₂ , 1-h maximum (µg/m ³)	CO, 8 h rolling average (mg/m ³)
1		0	0	0	0	0	0	0	0.0
1.015		1	21	10	38	30	33	51	3.9
1.031		2	41	20	77	60	67	102	7.9
1.046		3	62	30	115	90	100	153	11.8
1.061		4	83	40	153	120	133	204	15.7
1.077		5	104	50	192	150	167	256	19.7
1.092		6	124	60	230	180	200	307	23.6
1.107		7	145	70	268	210	233	358	27.5
1.123		8	166	80	307	241	267	409	31.5
1.138		9	186	90	345	271	300	460	35.4
>1.153		10	>207	>100	>345	>301	>333	>511	>39.3

The South African government has therefore developed a country-specific AQI that is aligned with international best practices, in order to translate the air quality recordings into simple language (DEA, 2012a). The AQI consists of five pollutants (PM₁₀, PM_{2.5}, NO₂, SO₂ and O₃), unlike the API by Cairncross et al. (2007), and it excluded CO because of its low ambient levels, even in priority areas within the country. The health levels of the AQI are divided into five, with bands ranging from 1-10:

- Low (1-3): indicates that a level of air pollution is unlikely to cause a negative effect on people who are exposed to short-term air pollution, including lung and heart diseases, and may be more sensitive to the effects of air pollution;
- Moderate (4-5): represents the levels of air pollutants in which there may be a small impact on susceptible people. However, the general public is unlikely to be affected.
- High (6-7): has a significant impact on sensitive people, but may not affect the general public. Very

High (8-9): those levels of air pollution, where even healthy individuals may experience adverse effects to short-term exposure. Members of sensitive groups may experience more serious health effects; and

- Hazardous (10): the level at which a health warning may be issued for an emergency situation, because all people are likely to be affected by serious health effects.

Table 2.7 Proposed banding of the SA AQI

AQ Level	Levels of health concern	Band	O ₃ 8-hour mean (µg/m ³)	NO ₂ 1-hour mean (µg/m ³)	SO ₂ 1-hour mean (µg/m ³)	PM _{2.5} 24-hour mean (µg/m ³)	PM ₁₀ 24-hour mean (µg/m ³)					
Low	Good	1	0-26	0	0-66	0	0-115	0	0-22	0	0-40	0
		2	27-53	27	67-133	67	116-231	116	23-43	23	41-80	41
		3	54-80	54	133-200	133	232-350	232	44-65	44	81-120	81
Moderate	Moderate	4	81-107	81	201-267	201	351-400	351	66-75	66	121-130	121
		5	108-134	108	268-334	268	401-450	401	76-85	76	131-140	131
High	Unhealthy	6	135-160	135	335-400	335	451-500	451	86-95	86	141-150	141
		7	161-187	161	401-467	401	501-550	501	96-105	96	151-160	151
Very high	Very Unhealthy	8	188-213	188	468-534	468	551-600	551	106-115	106	161-170	161
		9	214-240	214	535-601	535	601-650	601	116-125	116	171-180	171
Hazardous	Hazardous	10	>241	241	>602	602	>651	651	>126	126	>181	181

2.6 Conclusion

The chapter examines the background to air pollution and discusses the basic principles of air pollutants and their impact on human health through different studies. The impact of weather on air pollutants was also discussed. Air pollution is a global challenge, and the various management tools applied to reduce air pollution are discussed in this chapter. Finally, the tools introduced by South Africa for managing air pollution and ensuring that communities are not exposed to harmful air pollutants have also been discussed.

CHAPTER THREE

A REVIEW OF AIR POLLUTION AND HEALTH OUTCOMES FROM AMBIENT AND INDOOR SOURCES ACROSS THE ETHEKWINI AND MSUNDUZI MUNICIPALITIES IN SOUTH AFRICA

3.1 Abstract

Air pollution is an increasing global health crisis associated with the widespread health risks arising from exposure to contaminated air in the short and long term. Efforts to develop and improve resource equity in rural areas are often exacerbated by industrialization and urbanization, which lead to health risks associated with air pollution, both at spatial and geographical scales. Rural areas are mainly affected by indoor air pollution due to biomass burning. On the other hand, overcrowded urban areas are affected by various gaseous pollutants and the mixture of air pollutants from industries, transport sectors, landfills, biomass combustion and power plants. This review sums up the results of research on health outcomes attributed to poor air quality in the cities of eThekweni and Msunduzi in the province of KwaZulu-Natal, South Africa. The review includes literature from PubMed, Google Scholar, ResearchGate, and Science Direct databases. The evidence of the scientific publications reviewed indicates that communities close to sources of air pollution are the most exposed and most likely to develop respiratory diseases. The review also reveals that indoor and ambient air pollution and its health outcomes have not been investigated within the two municipalities, especially within the municipality of Msunduzi. Research is urgently needed to fill these knowledge gaps and assist in the development of better legislation and policies to support air quality management.

Keywords: indoor air pollution, ambient air pollution, human exposure, vulnerability, health

3.2 Introduction

The occurrence of respiratory diseases that are attributable to air pollution, especially ambient air pollution, are increasing globally. Various factors, such as an increase in industrial activities, household fuel combustion, transportation, as well as failure to implement air quality policies, have been cited as the main drivers of this situation (WHO, 2016). According to the World Health Organisation (WHO), air pollution has singly caused about 7 million premature deaths annually and there is no evidence that it is on the decline, despite guidelines being put in place to abate the associated health risks (Climate Transparency Report, 2020). The most-reported health risks associated with unabated air pollution are lung cancer, chronic bronchitis, heart disease, strokes, lower respiratory infections, cataracts, premature mortality and a low birth weight, among many others (Cohen et al., 2017). These health risks depend not only on the intensity of the exposure and the time that is spent being exposed, but also on how vulnerable and susceptible the individuals are. The socio-economic and demographic characteristics of the population have been cited as the drivers of the individual vulnerability to health risks associated with air pollution. Children under five years, the elderly and those living with pre-existing medical conditions are particularly vulnerable (Cohen et al., 2017). The criteria air pollutants that cause such health risks include particulate matter with an aerodynamic diameter of less than 2.5 and 10 micrometres (PM_{2.5} and PM₁₀), nitrogen dioxide (NO₂), sulphur dioxide (SO₂), carbon monoxide (CO) and ozone (O₃). The levels of some of these pollutants can be exacerbated by climate change, where photochemical reactions have been found to increase under high temperatures, especially for ozone (Doherty et al., 2009).

As highlighted by studies that link air pollution to health, the impacts of air pollution are a challenge in developing countries, particularly in low and middle-income countries (Schneidemesser et al., 2019; Gordon et al., 2014; Stieb et al., 2002; Ezzati and Kammen, 2001). These studies established further that the problem is more exacerbated in urban areas that are not just heavily populated, but hotspots of air pollutant emissions, especially those originating from traffic (Schneidemesser et al., 2019; Banerjee et al., 2012). Although South Africa (SA) is regarded as a developing country with booming industries and rapid urbanisation, it has been increasingly noted that the use of less clean energy has led to emissions, which have a detrimental impact on human health (DEA, 2019; Wright et al., 2017; Hanneman et al., 2016). Evidence from local studies has shown increasing emission levels of pollutants due to domestic and waste burning (Shezi and Wright, 2018), combustion in small industries (DEA, 2015; Morakinyo et al., 2017), vehicle emissions (DEA, 2019), heating and power generation (Shikwambana and Tsoeleng, 2019; Wernecke et al., 2015), landfill sites (Njoku et al., 2019) and mining activities (Norman et al., 2007a; Keen and Alteri, 2016). According to National Environmental Management: Air Quality Act 39 of 2004, Section 18(1) (SA, 2004), ambient concentrations may have the potential to exceed the National Ambient Air Quality Standards (NAAQS) (Shikwambana and Tsoeleng, 2019; Norman et al., 2007a; Norman et al.,

2007b; Keen and Altieri, 2016; Tshehla and Wright, 2019), particularly in the regions that have been declared as priority areas, such as the Vaal Triangle-Airshed Priority Area (VTAPA), the Highveld Priority Area (HPA) and the Waterberg-Bojanala Priority Area (WBPA) (Altieri and Keen, 2019).

The elevated concentration of ambient pollution from various pollutants is a significant concern for the people living in areas close to the sources that emit these harmful pollutants, such as the priority areas (DEA Chapter 10, (2016). Air pollution triggers, or causes, respiratory illnesses, which then result in death (Cohen et al., 2017). A report by Statistics South Africa (StatsSA, 2021) stated that 9.1% of the deaths in 2018 were caused by respiratory system illnesses. The G20 Climate Transparency Report (2020) stated that almost 23 000 people die in South Africa every year due to outdoor air pollution. Based on research by Keen and Altieri (2018), exposure to PM_{2.5} was associated with 6% of all reported deaths. Furthermore, a study by Norman et al. (2007a) projected that exposure to ambient air pollution in SA urban areas resulted in approximately 4 637 deaths in 2000. In the same year, the number of deaths attributed to indoor air pollution was 2 489 (Norman et al., 2007b). Therefore, the effective and efficient implementation of an air quality management plan in all spheres of government is required. According to the National Environmental Management Air Quality Act 39 of 2004 Section 15(1) (SA, 2004), it should be strengthened to assist in the reduction of air pollution and to prevent deaths.

According to Tshehla and Wright (2019), the KwaZulu-Natal Province (KZN) is one of the provinces in South Africa that has an underdeveloped air quality management plan, despite the fact that air quality deterioration has been reported in the province (DEA, 2015). Five of its cities, namely Pietermaritzburg, South of Durban, Newcastle, Estcourt and Richards Bay have been classified as the most-polluted cities in the province. Recent statistics in the province show that respiratory diseases and cardiovascular disorders are some of the top-10 leading underlying causes of death in the province (StatsSA, 2021). This is due to exposure to harmful air pollutants that are emitted from sources such as mining, landfill sites, industries, power-generating plants, transport and biomass fuel burning (Climate Transparency Report, 2020; Schneidmesser et al., 2019; Wernecke et al., 2015). Furthermore, the province hosts the busiest ports in Africa, which are the primary routes for imported crude oil, exported refined petroleum and petrochemical products (Mentz et al., 2018; Tshehla and Wright, 2019; Okello et al., 2018). Twelve sugar mills are located across the province (KZN DEA & RD, 2011), and the sugar farmers practise sugarcane burning during the harvest period; carbon-related smoke is released, which is a critical air pollutant in the atmosphere (Okello et al., 2018). In 2008, the KZN Province recognised sugarcane as being a significant and prominent source of air pollution in the province (KZN DEA & RD, 2011), especially in the area south of Durban, with its transportation emitting harmful air pollutants (Mentz et al., 2018; Naidoo et al., 2013).

It was reported that people living south of Durban under the eThekweni Municipality suffered from respiratory symptoms such as itchy noses and throats, burning and itching eyes and itching skin, which are associated with PM₁₀, PM_{2.5}, SO₂, NO₂ and O₃, as a result of exposure to air pollution from industries such as the petrochemical industry (Mentz et al., 2019). A study conducted by Kistnasamy et al. (2008) within the eThekweni Municipality found that children living south of Durban suffered from respiratory symptoms such as coughing, wheezing, chest tightness and shortness of breath. In Pietermaritzburg, fires at the New England Road landfill site during the winter season are a significant threat to human health (Naidoo, 2009). It was reported that communities living in areas close to air pollution sources, such as landfill sites, are at times reliant on asthma pumps (Nkosi et al., 2017).

Therefore, the state of air pollution and its impact on human health within the eThekweni and Msunduzi Municipalities indicate that there is a need to develop local customised solutions to avert such health impacts, particularly on vulnerable and susceptible individuals. In addition, deaths caused by respiratory diseases in KwaZulu-Natal are higher than those reported for the rest of South Africa (StatsSA, 2021). It is therefore essential to identify the local sources of emission and the related pollutants, and then to link them to the potential health effects in these municipalities. It is against this background that the objective of this study is to review published literature on ambient and indoor air pollution, and its associated health impacts in the eThekweni and Msunduzi Municipalities.

3.3 Methods

A systematic review approach was utilised to address the objectives of this thesis (Katoto et al., 2019; Snyder, 2019; Coker and Kizito, 2018). Literature was collected from the PubMed, Google Scholar, ResearchGate and Science Direct databases by using a combination of the following search terms: ‘air pollution and health’, ‘ambient air pollution on human health’, ‘respiratory impacts from air pollution’, ‘exposure to indoor and ambient air pollution’, ‘respiratory health from indoor and ambient air pollution’, ‘air pollution in KwaZulu-Natal’, ‘indoor air pollution and health outcomes’, ‘impacts of air pollution in the eThekweni Municipality’, ‘impacts of air pollution in the Msunduzi Local Municipality’, ‘air pollution in Pietermaritzburg’ and ‘air pollution in Durban’. Published articles that were written in English were searched. The reviewed articles that were considered were those conducted within the eThekweni District Municipality and the Msunduzi Local Municipality, as well as their surroundings.

The following selection criteria were adopted from Katoto et al. (2019):

- Study design: epidemiologic studies of any design, including cross-sectional, case-control, case-crossover and cohort studies;
- Outcomes: any human health findings;

- Exposure of interest: criteria pollutants (PM₁₀, PM_{2.5}, SO₂, NO₂, CO and O₃), measured either directly or inferred (e.g. by their proximity to roadways or landfill sites).’

In order to avoid limitations, no time-frame was considered during the reviews. Furthermore, a health outcome findings table was constructed, based on that of Katoto et al. (2019), which is shown in Table 3.1 below. While constructing the table, information was extracted from the selected studies: the analysis was based on any ‘sub-groups, reference, city/town, period, setting, design and type of the pollutant’. Health studies that were found to meet the selection criteria were also included in the analyses. The following data were extracted and included in the table: the author’s name, the year of publication, the country and city in which the study was performed, the study design, the year(s) of data collection, the type of controls (population-based, village-based), the sample size, the criteria pollutant exposure and the proximity to the emission sources, the type of outcomes (respiratory illnesses, etc), as well as the key conclusions of the authors (Katoto et al., 2019).

3.4 Results

Out of the fifteen (15) studies that were found, eight (8) had to be removed because they only reported the levels of air pollution and not the health outcomes from exposure to it. A total of seven (7) studies matched the selection criteria which looked at the health outcomes of air pollution exposure, especially criteria pollutants such as PM₁₀, PM_{2.5}, NO₂, CO, SO₂ and O₃ (refer to the flowchart in Figure 3.1).

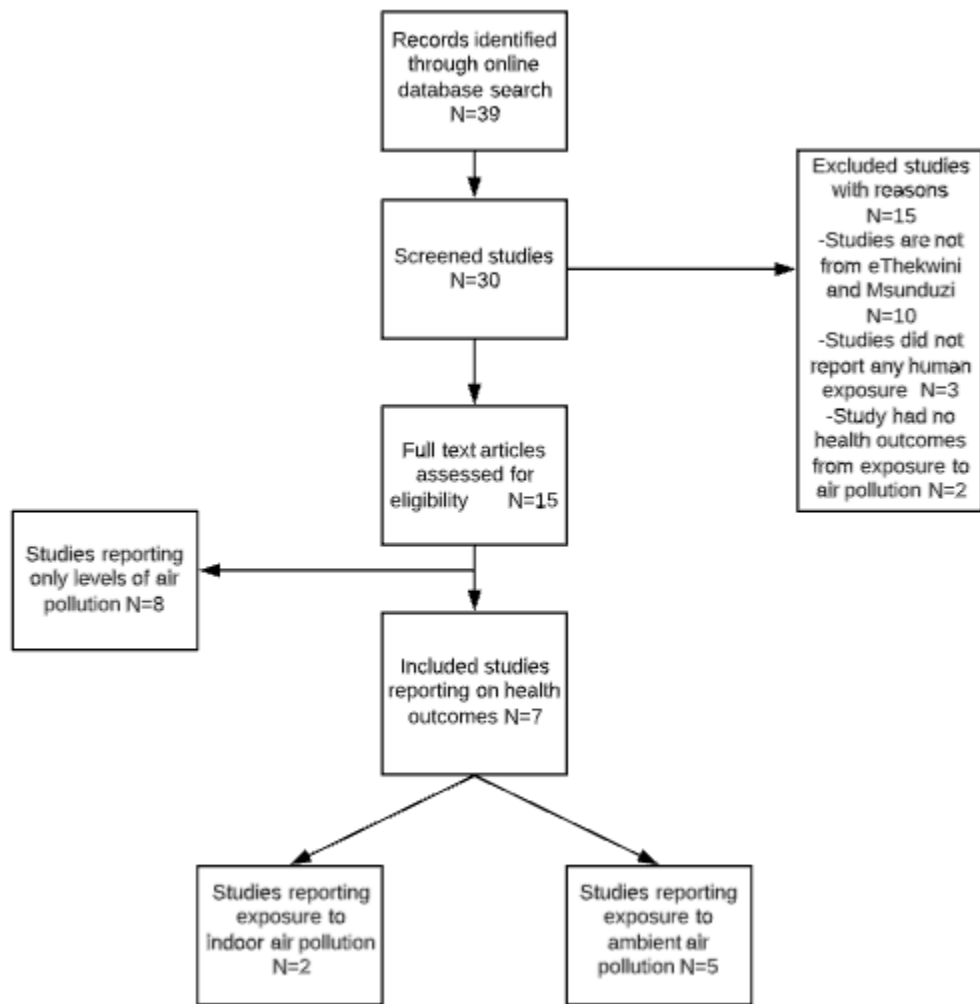


Figure 3.1 Flow diagram for selecting studies in both the eThekweni and Msunduzi Municipalities Table 3.1, which is adopted from Katoto et al. (2019), illustrates the health outcomes as a result of exposure to air pollution. Most of the studies represented in this table are from the eThekweni Municipality; however, one study conducted in Msunduzi did not meet our strict selection criteria, and therefore, it was not included in this table (refer to Table 3.1 for the summary findings).

Table 3.1 Summary of respiratory outcomes findings

Health Outcome	Age	Reference	Study Area	Method	Exposure	Summary of the main conclusions
Hay fever	All ages	Buthelezi et al. (2019)	KwaZulu-Natal, Durban, Umlazi Township	Cross-sectional	Particulate matter	Upper respiratory tract infections were more prevalent in households using biomass fuel sources, such as wood, and fossil fuels, such as paraffin, coal and gas used for domestic purposes, such as cooking and heating.
	Children	Naidoo et al. (2013)	KwaZulu-Natal, Durban	Cross-sectional	PM ₁₀ and SO ₂	A total of 11.5% of all school children were diagnosed with hayfever by doctors.
Wheeze	All ages	Buthelezi et al. (2019)	KwaZulu-Natal, Durban, Umlazi Township	Cross-sectional	Particulate Matter	Lower Respiratory Tract Infections (LRTI) were reported to be higher among respondents that used other fuels (coal, wood, paraffin and gas) for space heating.
	Children	Mentz et al. (2018)	KwaZulu-Natal, Durban	Cross-sectional	NO ₂ , NO, SO ₂ , CO, O ₃ , PM _{2.5} and PM ₁₀	School children from industrialised and higher traffic areas within the school vicinity reported respiratory symptoms, such as wheezing.
	Children (6-12 years)	Gumede and Savage, (2017)	KwaZulu-Natal, Durban, Clare Estate	Cross-sectional	PM _{2.5}	Children from the Clare Estate, which is near the Bisasar Road landfill site, suffered from wheezing.

Health Outcome	Age	Reference	Study Area	Method	Exposure	Summary of the main conclusions
	Children	Naidoo et al. (2013)	KwaZulu-Natal, Durban	Cross-sectional	PM ₁₀ , SO ₂	The study found approximately 24% of wheezing was reported on children, meanwhile 41.5% of children, mostly in the south of Durban, reported attacks of wheezing.
Asthma	All ages	Buthelezi et al. (2019)	KwaZulu-Natal, Durban, Umlazi Township	Cross-sectional	Particulate matter	The use of fossil fuels, such as coal, for cooking and space heating in low-income communities, such as townships, have been found to contribute to the increasing occurrence of respiratory symptoms.
	Children	Mentz et al. (2018)	KwaZulu-Natal, Durban	Cross-sectional	NO ₂ , NO, SO ₂ , CO, O ₃ , PM _{2.5} and PM ₁₀	Concentrations of NO _x and SO ₂ showed a significant spread due to the higher density of air pollution sources (industries and an increase in vehicles) in the south of Durban. Children living south of Durban reported more cases of asthma attacks, compared to those living in the north.
	Children (6-12 years)	Gumede and Savage, (2017)	KwaZulu-Natal, Durban, Clare Estate	Cross-sectional	PM _{2.5}	Children living +/- 2 km away from a landfill site were diagnosed by doctors to have asthma within the past 12 months.
	Children	Makamure et al. (2017)	KwaZulu-Natal, Durban	Cross-sectional	PM ₁₀ , SO ₂ , NO ₂ , and NO	35% of the children reported asthma-related symptoms in the south of Durban, where the highest concentration of SO ₂ has been measured.
	Children	Naidoo et al. (2013)	KwaZulu-Natal, Durban	Cross-sectional	PM ₁₀ , SO ₂	Persistent asthma symptoms were reported mostly by children attending schools in the south of Durban.

Health Outcome	Age	Reference	Study Area	Method	Exposure	Summary of the main conclusions
	Children	Mentz et al. (2019)	KwaZulu-Natal, Durban	Panel	NO ₂ , NO _x , PM ₁₀ , SO ₂	NO _x levels in the south were significantly higher (p<0.001), due to emissions from vehicles. The emitted NO _x was reported to be associated with a decrease in acute lung function in schoolchildren.
Bronchitis	Children (6-12 years)	Gumede and Savage, (2017)	KwaZulu-Natal, Durban, Clare Estate	Cross-sectional	PM _{2.5}	About 8% of children living near the landfill site were diagnosed with chronic bronchitis.
	Children	Naidoo et al. (2013)	KwaZulu-Natal, Durban	Cross-sectional	PM ₁₀ , SO ₂	Bronchitis was observed to be associated with an increase in PM ₁₀ and SO ₂ .
Pulmonary Tuberculosis (PTB)	Children (0-14 years)	Jafta et al. (2019)	KwaZulu-Natal, Durban	Case-control	Second-hand smoking, PM ₁₀ , NO ₂	Indoor air pollution exposure due to house dampness, second-hand smoke and the use of fossil fuels for cooking and space heating, were reported to be linked to acquiring PTB in children.

3.4.1 Exposure measurements

Most of the studies in Table 3.1 installed air quality monitoring stations within the school premises to measure the criteria pollutants (PM₁₀, PM_{2.5}, NO₂, SO₂, CO, O₃), while some used governmental air quality monitoring stations (Mentz et al., 2018; Naidoo et al., 2013; Gumede and Savage, 2017; Jafta et al., 2019). Mentz et al. (2018) and Makamure et al. (2017) used ultraviolet fluorescence spectrometry to monitor SO₂, while a HAZ-Dust particulate monitor was used to measure indoor PM_{2.5} (Gumede and Savage, 2017). Other studies used predictive models to estimate the PM₁₀ and NO₂ (Jafta et al., 2019). Almost 90% of the studies measured criteria pollutants from schools south of Durban, which is regarded as a highly-industrialised area, compared to schools that are found north of Durban (Naidoo et al., 2013; Makamure et al., 2017; Mentz et al., 2018).

3.4.2 Health-related outcomes

3.4.2.1 Ambient air pollutants and respiratory health

Mentz et al. (2018) used a random selection method on Grade Four (4) classrooms at seven (7) primary schools in Durban (on the southern and northern sides of Durban). The study used a total sample of 423 participants, including asthmatic children. The ambient pollutants measured throughout the study were NO₂, SO₂, CO, O₃ and PM₁₀. The study found that there is a relationship between exposure to numerous pollutants and respiratory symptoms, such as coughing. An increase in exposure to PM₁₀, PM_{2.5}, SO₂, NO₂ and CO concentrations was found to be linked to increased respiratory symptoms, such as coughing, shortness of breath and tightness of the chest. On the other hand, wheezing was commonly associated with an increase in the NO₂ concentration among the school children. In addition, most of the respiratory symptoms were reported in schools to the south of Durban, rather than schools to the north.

Another study by Naidoo et al. (2013) investigated air pollution exposure in Grade Four (4) learners in primary schools located both south and north of Durban, it should be noted that these schools are located in the same area that Mentz et al. (2018) investigated in their study. Air pollutants, such as NO₂, NO, SO₂, PM₁₀ and PM_{2.5}, were measured in the schools over a period of eight (8) months. A total number of 341 children participated in the study. This study found that the SO₂ concentration was much higher in schools located in the south of Durban, compared to schools in the north. The persistent respiratory symptoms that were found were hayfever (11.5%) and wheezing (24%), with the worst cases being wheezing attacks. Asthma and bronchitis were associated with an increase in PM₁₀ and SO₂. A total of 24% children were reported to have wheezing symptoms, with 41.5% reporting attacks of wheezing with dyspnoea in schools to the south of Durban.

A total number of 423 children attending school in the south of Durban, which is classified as highly-polluted due to air pollution from sources such as industries and transportation, were included in a study by Mentz et al. (2019). This study measured NO₂, NO_x, SO₂ and PM₁₀ at seven (7) school sites and found that NO₂ and NO_x had the highest concentration levels from June to September. On the other hand, the mean concentration levels of PM₁₀ and SO₂ did not exceed that of the World Health Organisation guidelines (WHO, 2005) and the South African Air Quality guidelines (South Africa, 2009). Moreover, the increase in NO₂ and NO was associated with an increase in asthmatic reactions among the schoolchildren.

The SO₂, PM₁₀, NO₂ and NO pollutants were also measured in schools in Durban south (Makamure et al., 2017). The study had 71 children who participated in the survey. This study estimated the relationship between the daily air pollutant levels and (the cluster of differentiation) CD14 cell genetic polymorphisms within-day changes in lung function. Seven schools and children who were an average of 10 years of age, were included in this study. It was found that the SO₂ levels varied widely across the study area, and the highest concentrations occurred in the south of Durban, where the highest number of industries are located. The study also found that 37% of children frequently reported asthmatic symptoms.

Air pollution has also been identified as a contributing factor to respiratory illnesses in the Msunduzi Local Municipality, although no studies could be found in the review that linked health outcomes and air pollution. A study within the municipality, which studied “healthcare utilisation” for respiratory diseases, found that diabetes was the underlying condition within the Msunduzi Municipality, followed by asthma, which is a respiratory illness (McAnerney et al., 2019). The study also revealed that people with pre-existing medical conditions, like Human Immunodeficiency Virus (HIV) infections, were likely to report cases of pneumonia or chronic febrile respiratory illness (McAnerney et al., 2019). This provides evidence that people with pre-existing medical conditions are more vulnerable when exposed to air pollution (Jafta et al., 2019). This municipality is home to several industries, such as KZN Tissue, which is based in Mkondeni, where cases of wind-blown particulate matter were reported (DEA, 2015). In comparison, a study conducted in Gauteng revealed that communities living in close proximity to mine dumps are likely to be exposed to criteria air pollutants that are transported by means of wind or thermal combustion, which may trigger or cause respiratory illnesses, especially in vulnerable groups such as the elderly and children (Nkosi et al., 2019; Nkosi et al., 2016). Such indicators could refer to complaints of a bad odour coming from the Willowton Oil and Cake Mill and Epol industries, which were reported by a nearby community in the Msunduzi Municipality (DEA, 2015).

3.4.2.2 Indoor air pollution and respiratory health

Twenty-three (23) children, ranging between 6 and 12 years old, were studied in a study by Gumede and Savage (2017). This study investigated indoor air pollution in houses in Clare Hills, near the Bisasar landfill site in the eThekweni Municipality. The PM_{2.5} records indicated that 157 µg m⁻³ was mostly recorded, which exceeds the WHO guidelines. The study found that 65% of the children residing near the Bisasar Road landfill site reported respiratory diseases such as asthma, chronic respiratory diseases, coughing, and coughing, (Gumede and Savage, 2017). In 2017, an average force exhaustion volume of 1 s (FEV1) was 82 %, an average force capability (FVC) of 75 %, and an average force capacity (FEV1/FVC) of 115 %. The average indoor concentration of PM_{2.5} is 76.5 g m³ and 202 g m³. Furthermore, using regression models, significant statistically strong correlations ($p < 0.002$) were found between the indoor concentration of PM_{2.5} and the FVC. Therefore, this gives a clear indication that communities living close to a landfill site are exposed to a high concentration of air pollutants, and they are therefore more susceptible to respiratory illness.

The study by Jafta et al. (2019) collected data on children's health, household characteristics and sources of household air pollution (the domestic fuel used and second-hand smoke exposure) by using questionnaires. The PM₁₀ and NO₂ were measured inside the households for a period of two to three weeks. The study found that PM₁₀ concentrations were significantly higher in homes where caregivers had a lower level of education, and that NO₂ and PM₁₀ concentrations were also higher in informal and households using dirty cooking fuels (e.g coal, wood, animal dung and grass) . Furthermore, it was found that dampness at home, exposure to second-hand smoke and the use of dirty cooking fuel in households were associated with early childhood pulmonary tuberculosis (PTB).

Another study of fuel use and respiratory health was conducted in Umlazi, Durban, with 245 households (Buthelezi et al., 2019). The survey found that 62% of households used electricity, while 18% relied on paraffin. Most people use dirty fuels to heat their homes. Upper respiratory tract infections (URTI, n = 27) are common among people who use non-electric sources for heating and cooking compared to electric sources. Non-electrical sources had statistically significant effects on the incidence of URTI in cooking (OR adjusting = 3.6, 95% confidence interval: 1.2–10.1, $p < 0.05$) and cooking (OR adjusting = 2.9, 95% confidence interval: 1.1–7.9, $p < 0.05$). However, Buthelezi et al. (2019) found that heating sources had a statistically significant impact on the prevalence of lower respiratory infections (OR adjusted to 2.7, 95% confidence interval: 1.1–6.4, $p < 0.05$), but there was no evidence of a relationship between non-electric heating sources and LRT, and the types of non-electric cooking fuels and LRT.

3.5 Discussion

The review focuses mainly on school environments, but little research has been done on other communities in other municipalities to investigate the relationship between air pollution and health effects. Most of the studies in this review reported that ambient air pollution south of Durban exceeds that of the WHO and NAAQS. The south of Durban is characterised as an industrialised area, just like other areas, such as eMalahleni in Mpumalanga (Wernecke et al., 2015; Shikwambana and Tsoeleng, 2019), where communities are reporting respiratory illnesses caused by various industrial activities. Similarly, where communities in Msunduzi complained of bad odours from the England Road landfill site, they reported respiratory symptoms such as itchy eyes, runny noses, tightness of chest and wheezing, to name a few. Therefore, due to the health outcomes from air pollution in these municipalities, it is recommended that stricter standards should be applied, in terms of their municipal by-laws, according to the National Environmental Management Act (South Africa, 2004).

This review found that the majority of the previous studies have concentrated on children and only a few have considered other age groups. None of the studies in these municipalities focused on how air pollution impacts the health of the elderly population, in order to give a broader picture, since they are part of a vulnerable group. A study by Nkosi et al. (2017), in an urban setting in Gauteng and Northwest, found that the elderly living close to air pollution sources, such as mine dumps, reported respiratory illnesses like asthma and pneumonia. There is therefore a need to include the elderly age groups in future research on health impacts from air pollution within the eThekweni and Msunduzi Municipalities. It is recommended that tighter policies need to be implemented by local governments to assist in reducing air pollution. Tshehla et al. (2018) recommended that politicians need to be educated on air quality matters, since they are the main drivers of policy implementation. Municipalities need to have tools, such as an air quality early warning tool, during increased levels of air pollution, that they can use to inform the public, especially vulnerable groups, on how to prevent the respiratory illnesses that are being triggered.

This review had its limitations, in terms of the possibility that some published articles that were not in the PubMed, Google Scholar and Research Gate databases, may have been missed. Most of these studies were concentrated on the eThekweni Municipality. No study could be found which looked at the health outcomes of air pollution in the Msunduzi Local Municipality. However, one study conducted within this municipality did give a health overview of the diseases reported by its communities (McAnerney et al., 2019) that may have been caused by the high concentration levels of the air pollutants that they are exposed to. More studies are required in this municipality that will link air pollution and respiratory health, especially in areas that are close to air pollution sources, such as industries, biomass burning, fuel burning, power generating stations and transportation.

3.6 Conclusion

Kwa Zulu-Natal (KZN) has the highest number of cases of underlying health conditions, which explains there is higher death rate in South Africa associated to health risks from air pollution. This study revealed that the eThekweni Municipality is facing indoor and outdoor air pollution and that the main drivers are from landfill sites, the burning of dirty fuel for both cooking and space heating, as well as emissions from various industries. The results on the exposure and health outcomes are still scanty and more studies are needed to fill the existing epidemiological knowledge gaps, especially in the Msunduzi Local Municipality. An awareness of the issues regarding the existing air pollution and the potential health outcomes needs to be enhanced and supported at a policy level by the relevant municipalities. The need for indoor air pollution guidelines is critical and should be put in place to assess harmful health impacts on personal exposure from indoor air pollution. An air quality early warning system will need to be developed to identify the exposure to ambient air pollution in these municipalities, in order to inform communities on what to do in the case of symptomatic health conditions that are potentially linked to harmful air pollutants.

CHAPTER FOUR

METHODOLOGY

4.1 Introduction

The aim of this chapter is to provide a detailed description of the research area, materials used and procedures for achieving the research goals and objectives. The data sets used and their sources are first described, followed by the procedures used to process the data, extract potentially predictive variables, and apply statistical analysis to develop the most appropriate air quality index.

4.2 Study Sites

4.2.1 The eThekweni Metropolitan (the primary site)

The Municipality of eThekweni is located on the east coast of South Africa in KwaZulu-Natal. The Municipality has an area of about 2 297 kilometres and about 3 442 361 inhabitants (Census 2011). The Municipality is located in a region that receives approximately 1 009 mm of rainfall, with rainfall occurring during the summer season. The temperatures are between 16 and 25 degrees Celsius in winter and 23 and 33 degrees Celsius in summer.

The air quality within the Metropolitan of eThekweni is poor, due to the booming industries in Durban (Mentz et al., 2019). There are a number of sources of air pollution in the region, namely, industries, landfills, biomass combustion, transport and household fuel combustion (Botes and Mckenzie, 2013). Air pollution from the Durban landfills has resulted in respiratory symptoms in schoolchildren living near the landfill sites (Gumede and Savage, 2017). Exposure to air pollutants from various industries, such as NO₂, NO, SO₂, CO, O₃, PM_{2.5} and PM₁₀, has been associated with coughing, breathing problems and chest tightness in schoolchildren in Durban (Mentz et al. 2018). Figure 4.1 demonstrates location of the eThekweni Municipality and the distribution of the air quality stations.

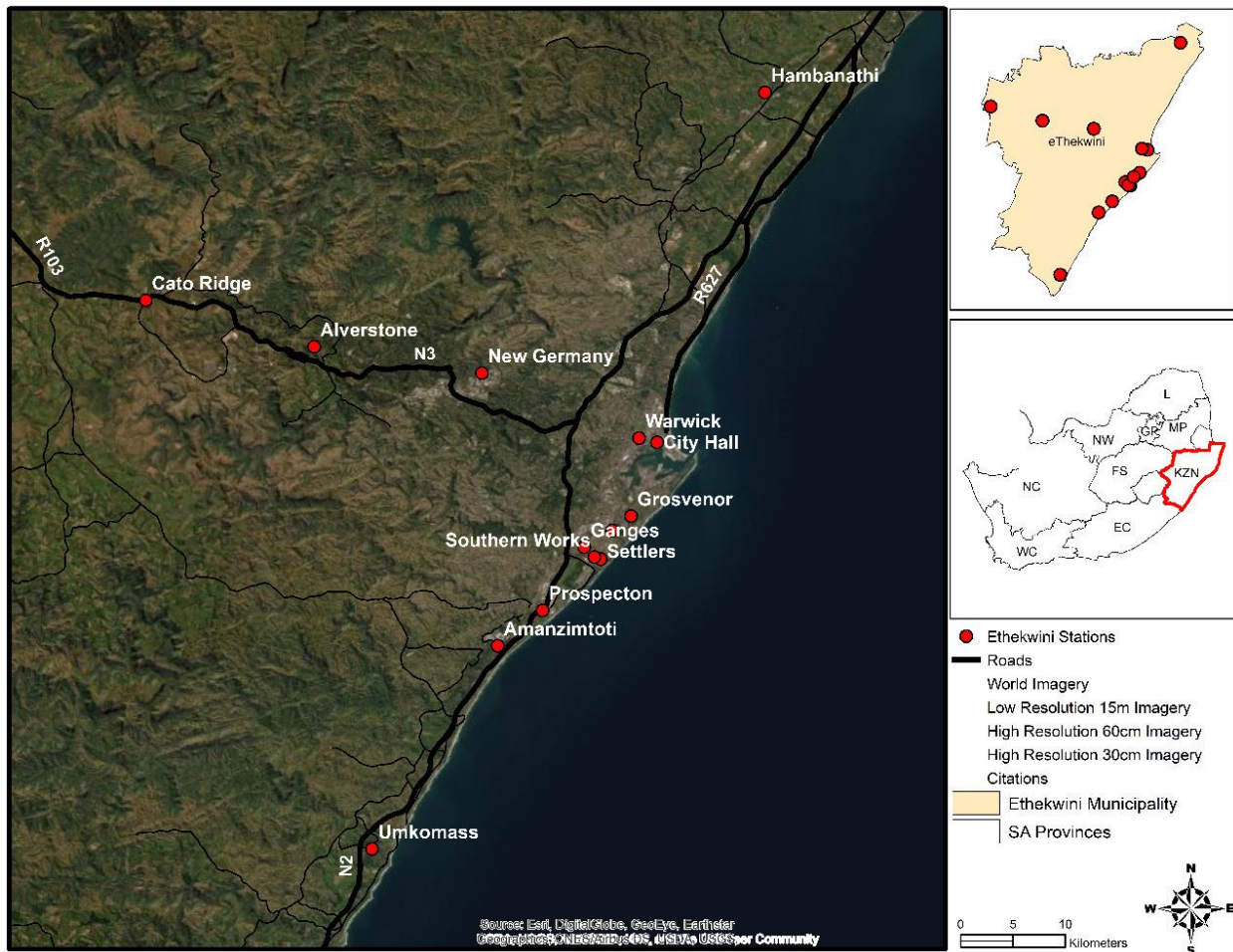


Figure 4.1 Map of the eThekweni Municipality

4.2.2 The Msunduzi Local Municipality (the secondary site)

The Msunduzi Local Municipality is located within the Municipality of the UMgungundlovu District, along the N3 at the junction of two corridors, from Durban to Estcourt and from Greytown to Richmond (Msunduzi Local Municipality, 2018). This municipality is located in a region that receives more rainfall during the summer season. It varies from approximately 758 mm to 986 mm (Winnar, 2017). The average maximum temperature in the municipality is 22.6 to 24.5 degrees Celsius and the minimum temperature is 9.9 to 16 degrees Celsius (Hlahla and Hill, 2018). The main city is Pietermaritzburg, which is also the legislative capital of KwaZulu-Natal. The Msunduzi Municipality is home to a total population of 618 536.

The air quality in the Msunduzi Local Municipality has been deteriorating, due to the anthropogenic and natural emission sources. The main sources of air pollution in this region are fuel biomass combustion, the high volume of traffic along the N3 highway, because it joins two of the busiest big cities in South Africa (Durban and Johannesburg), the landfill site (which is situated about one kilometre east of the CBD), as well as the surrounding sugarcane-burning practices (UMDM, 2013). The human implications of sugarcane

burning are outlined in a presentation by Puckree and Mthembu (2018), which shows that the particles that fall during the burning of sugarcane deteriorate the air quality and impact human health by irritating the respiratory system. According to a study by McAnerney et al. (2013), about 72% cases of pneumonia and chronic febrile respiratory illnesses were reported in the Msunduzi Local Municipality. Figure 4.2 below shows the location of the Msunduzi Municipality and the distribution of the air quality stations.

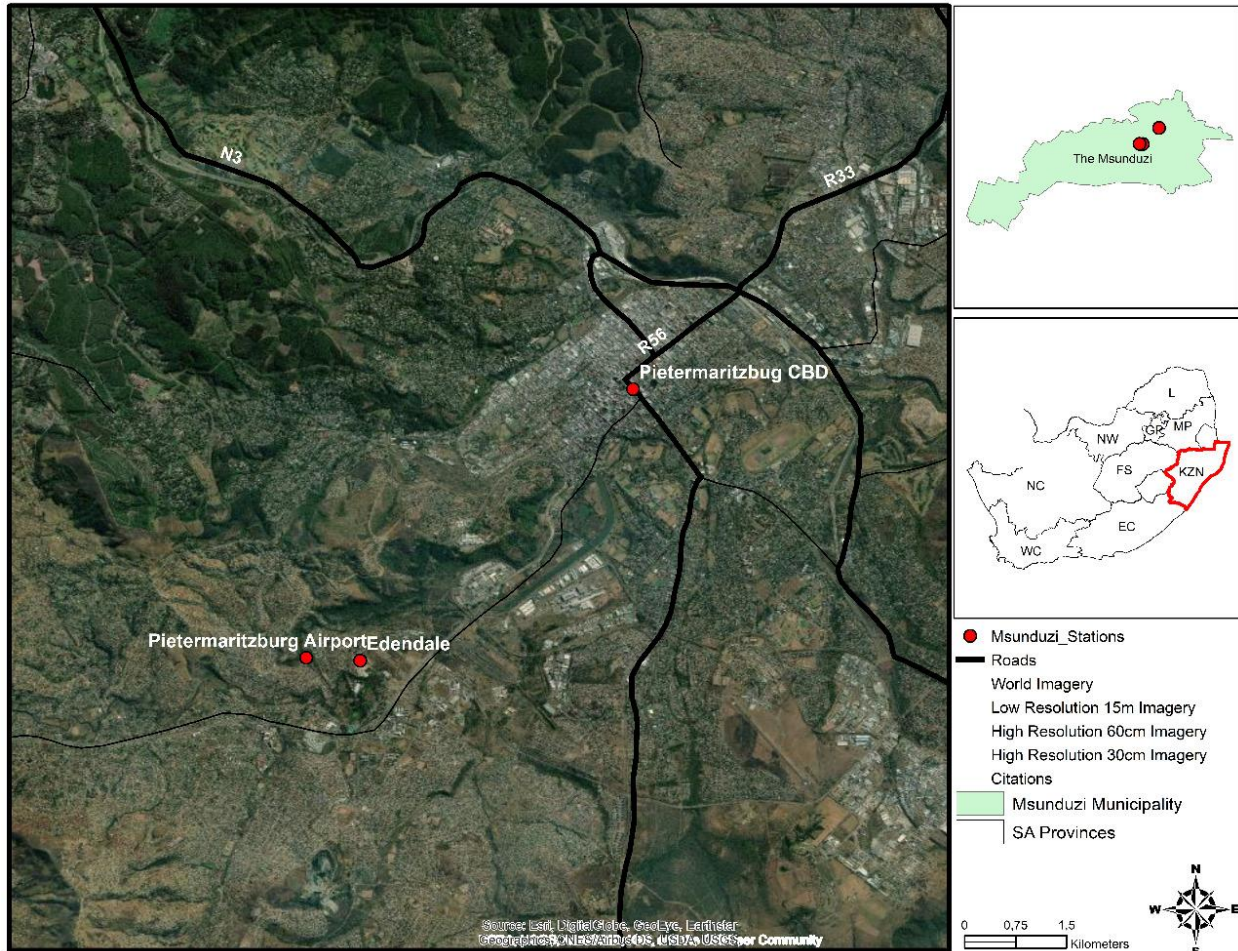


Figure 4.2 Map of the Msunduzi Municipality

4.3 Dataset

- Hourly observation data of the air quality were obtained from the SAAQIS.
- Meteorological data (surface temperature, relative humidity, wind direction and wind speed) have been obtained from SAAQIS.

4.4 Analysis Method

4.4.1 To determine the air pollution exceedances and spatial distribution of criteria air pollutants at the eThekweni and Msunduzi Municipalities

This study used near real-time air quality data from the government stations located in the Msunduzi and eThekweni Municipalities. These data were downloaded from the SAAQIS (<https://saaqis.environment.gov.za/>) for 1 January 2020 to 31 December 2020 to determine the level of air pollutants within them. IBM SPSS Statistics Version 27 was used to analyse collected data by applying descriptive statistics. Descriptive statistics enabled this author to summarise and describe the collected data (Thompson, 2008).

Hourly air quality data was used and were then converted to 24-hour mean for pollutants such as SO₂, CO, PM₁₀ and PM_{2.5}. The 24-hour mean for these pollutants was calculated to determine air quality in the area, and National Ambient Air Quality Standards (NAAQS) (DEA, 2009) and the World Health Organisation (WHO) guidelines (WHO, 2021) were established as a boundary point, to determine the number of exceedances.

The data on air pollutants in the eThekweni and Msunduzi Municipalities, such as SO₂, NO₂ and O₃, are presented as parts per billion. Therefore, for this study, guidelines from the World Health Organisation were converted from micrograms per cubic meter (µgm⁻³) to parts per billion (ppb). Conversions of micrograms per cubic meter (µgm⁻³) to parts per billion (ppb) were calculated in the Terrie and Boguski (2006), using Equation (4.1) below:

$$\text{Concentration (ppb)} = 24.45 \times \text{concentration (ug / m}^3\text{) /molecular weight} \dots\dots\dots (4.1)$$

Table 4.1 National Ambient Air Quality Standards (NAAQS) and World Health Organisation (WHO) Guidelines

Parameter	Averaging period	Concentration	Number of exceedances
PM ₁₀	NAAQS 24-hour	120 µg/m ³	4
	WHO 24-hour	45 µg/m ³	
PM _{2.5}	NAAQS 24-hour	65 µg/m ³	4
	WHO 24-hour	15 µg/m ³	
SO ₂	NAAQS 24-hour	48ppb	4
	WHO 24-hour	15ppb	
NO ₂	NAAQS 1-hour	106 ppb	0
	WHO 1-hour	106 ppb	
O ₃	NAAQS 8-hour	61 ppb	11
	WHO 8-hour	51 ppb	

Data are then classified into four seasons, starting with summer (December, January, February), autumn (March, April, May), winter (June, July, August), and spring (September, October, November). The seasonal data were compared to the NAAQS and WHO thresholds and mapped to bar charts to determine trends in air pollution concentrations and the number of days of excess.

Thereafter, Arc GIS was used to quantify the spatial distribution of the air pollutants within the Municipalities (Bezyk et al., 2021; Li and Heap, 2008). Using ArcGIS software, the air quality parameter dataset was imported to ArcMap as an Excel file and was converted to a point shape file with x, y, z coordinates, using the WGS 1984 coordinate system. The analysis was performed by interpolating the data points of the mapped stations based on air quality parameters in order to create a raster surface at the study site. Kriging raster interpolation was used, to analyse the changes in the spatial extent of the air quality parameters (Tyagi and Singh, 2013). These observations were examined, based on an average daily parameter.

4.4.2 To determine the relationship between the meteorological parameters and air pollution at eThekweni and Msunduzi sites

The stations selected for this analysis were those that record the meteorological parameters (wind speed, wind direction, temperature and relative humidity) and air pollutants (PM_{2.5}, PM₁₀, SO₂, O₃ and NO₂). IBM SPSS Statistics Version 27 was used to determine Pearson correlation between meteorological parameters and to determine the level of air pollutant concentrations within the municipalities (Radulescu et al., 2019). A multiple linear regression was used to predict the relationship between air pollutants and meteorological parameters. The general equation (Equation 4.2) of the model is found below:

$$y = b_0 + \sum_{i=1}^n b_i x_i + \varepsilon \quad \dots\dots\dots (4.2)$$

where b_i is a regression coefficient, X_i is explanatory variables (predictors) and ε is the stochastic error associated with regression (Kovač-Andrić, 2011). The study adopted the standard value of $p < .05$ as significant at 2-tailed and an acceptable strong relationship of 70%/0.7 (Peter, 2014). Wind speed and direction data was used to create a wind rose (Elangasinghe et al., 2016), and the Open-air package was used to plot the wind roses (Carslaw, 2019). The monthly wind rose plots were plotted to show how the wind speed and wind direction conditions varied by season within the study area.

4.4.3 To develop an Air Quality Index as an early warning system for the eThekwini Metropolitan and Msunduzi Local Municipalities

Air quality data from stations located within the eThekwini and Msunduzi Municipalities were used to develop an Air Quality Index (AQI), which will then be used as an Air Quality Early Warning System. The US EPA method is a widely-used method for developing an AQI; for example, it has been used in Finland by Hämeikoski (1998), while Osimobi et al. (2019) developed an AQI for the university campus in Nigeria, and Bishoi et al. (2009) used this method in a comparison study at the Jawaharlal Nehru University (JNU) Campus in India,

The eThekwini Metropolitan Municipal Air Quality Index (eThAQI) and the Msunduzi Local Municipal Air Quality Index (MsuAQI) focus on the health effects people can experience in hours or days after breathing unhealthy air (EPA, 2014). AQI is calculated for 5 air pollutants that are regulated by PM₁₀, PM_{2.5}, NO₂, O₃ and SO₂. This study will exclude CO as the National AQI because of its low emission concentration levels (DEA, 2012a), as recommended by the US EPA (2014) and the EPA technical report (EPA, 2018). The AQI is calculated on the basis of sub-indices and health effects specific to pollutants, based on the NAAQS and WHO guidelines (DEA, 2012a; Thach et al., 2018; EPA, 2018). The eThAQI and MsuAQI are divided into six levels of health concerns, with bandings that range from 0-500 and health messages that advise both the sensitive population and the general public (EPA, 2014; Stieb et al., 2008; Wong et al., 2013):

Table 4.2 Health messages for eThAQI and MsuAQI

Levels of health concerns	Health Messages	
	Sensitive group	General group
Good (0-50)	Enjoy can your usual outdoor activities	No health-risk conditions, are good for outdoors activities (hiking, biking and those working outdoors)
Moderate (51-100)	If you suffer from heart disease and respiratory disease and experience symptoms, reduce outdoor exercise and re-record activities to times when the index shows a "good" signal.	You don't have to change the usual outdoor activities.
Unhealthy for sensitive groups (101-150)	Children, people over the age of 65 and those with heart or breathing problems should reduce or re-schedule their outdoor activities to low index periods, especially when they are experiencing symptoms.	Little or no health risk for the general public
Unhealthy (151-200)	Children, older people and people with heart disease and respiratory diseases (such as heart disease and other heart disease, asthma, chronic respiratory obstruction, chronic bronchitis, etc.) should reduce physical exertion outside, especially in heavy traffic areas.	Anyone suffering from discomfort (such as cough or throat inflammation) should consider reducing or rearranging intense outdoor activities to periods when the index is lower.
Very Unhealthy (201-300)	Children, elderly people, and those with heart or breathing problems should avoid physical exercise at home.	Everybody must consider reducing or rescheduling strenuous outdoor activities, especially if they experience symptoms.
Hazardous (301-500)	People with heart disease and respiratory disease should avoid physical exertion outside and avoid staying outside, especially in areas with a lot of traffic.	It is recommended that people limit their outdoor activities and restrict their outdoor stay, especially in areas where traffic is high.

The AQI will be calculated by using the following formula, which was adopted from the U.S. Environmental Protection Agency in Equation (4.3) below:

$$AQI = \left[\frac{AQI_{max} - AQI_{min}}{BP_{max} - BP_{min}} (C_p - BP_{min}) + AQI_{min} \right] \dots \dots \dots (4.3)$$

Where:

C_p = daily observed reference concentration of pollutant p,

BP_{max} = the lowest break point of the pollutant p that is greater than or equal to C_p ,

BP_{min} = the highest breakpoint of the pollutant p that is less than or equal to C_p ,

AQI_{max} = the AQI value corresponding to the BP_{max} of the pollutant p, and

AQI_{min} = the AQI value corresponding to BP_{min} of the pollutant p.

In order to evaluate the AQI at the monitoring station where more pollutants are measured, the EPA procedure assumed maximum AQI of a single contaminant at the location (EPA, 1999; EPA, 2018). Equation (4.4) was then adopted, where AQI_s is the Air Quality Index per station (EPA, 2018):

$$AQI_s = \max(AQI) \dots \dots \dots (4.4)$$

The calculated AQI_s were then grouped into four seasons (summer, autumn, winter and spring) (Kumar and Dash, 2018; Udoh and Umoh, 2018).

4.5 Conclusion

This chapter has presented the study area (the eThekweni and Msunduzi Municipalities) and it has further illustrated the total area in which the municipalities are located, their populations, rainfall and temperatures. The air quality monitoring stations were also illustrated. This chapter further discussed the datasets that were used in this study and the sources of the data. Furthermore, the study described, in detail, the analysis approaches that the study would undertake, as well as the proposed Air Quality Index and indicators that would assist the public to prevent exposure to harmful air pollutants.

CHAPTER FIVE

RESULTS

5.1 Introduction

The aim of this chapter is to provide statistical graphics, tables and descriptions of the results obtained in this study. First, exceedances of air pollution using WHO and NAAQS as thresholds, as well as the spatial distribution of pollutants. Thereafter, the study presents the correlation between air pollutants and meteorological factors, like wind direction, wind speed, temperature and relative humidity. The proposed Air Quality Index is presented as an early warning system for eThekweni and Msunduzi Municipalities.

5.2 Air Pollution Exceedances and Spatial Distribution of Criteria Air Pollutants

5.2.1 Air quality exceedances

5.2.1.1 City Hall

PM_{2.5} concentrations

The City Hall air quality monitoring station recorded an overall highest peak of 83.159 $\mu\text{g}/\text{m}^3$ in July 2020. In summer, the station recorded the highest peak of 17.04 $\mu\text{g}/\text{m}^3$. In autumn (May), the station recorded a highest peak of 40.43 $\mu\text{g}/\text{m}^3$, while in winter (July), the station recorded the highest peak of 83.159 $\mu\text{g}/\text{m}^3$. Lastly, the station recorded a highest peak of 34.43 $\mu\text{g}/\text{m}^3$ in September during the spring season (refer to Figure 5.1).

PM_{2.5} Exceedances

The WHO and NAAQS limits were used as thresholds to determine the exceedances (refer to Figure 5.1). During the summer season, only one exceedance was recorded in January, when compared to the WHO, and there were none, when compared to NAAQS. During autumn, 2 and 15 exceedances were recorded in April and May, respectively, when compared to the WHO guidelines. During winter, 1 and 14 exceedances were recorded in June when compared to the NAAQS and WHO. In July, there were 10 and 22 exceedances compared to the NAAQS and WHO, respectively. In August, the station recorded 2 and 14 when compared to the NAAQS and WHO thresholds, respectively. During spring, 5 exceedances were recorded in September when compared to the WHO, and no exceedances were recorded that were higher than that of the NAAQS. 9 exceedances were recorded in October when compared to the WHO, no exceedances were recorded when compared to the NAAQS, and in November, 2 exceedances were recorded when compared to the WHO and NAAQS.

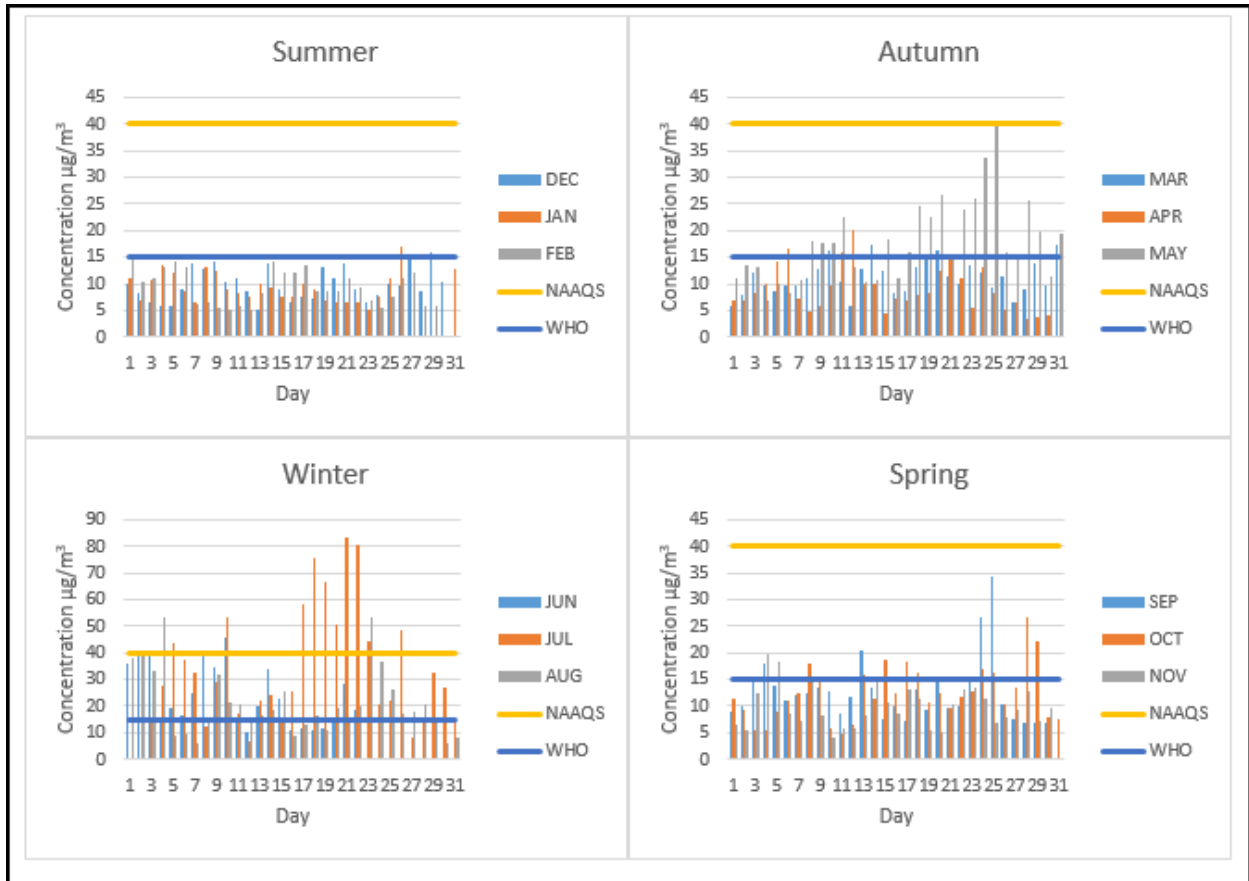


Figure 5.1 City Hall PM_{2.5} 24-hour average concentration

5.2.1.2 Settlers

PM_{2.5} concentrations

The Settler air quality monitoring station recorded an overall highest peak of 110,746 µg/m³ in July 2020 (refer to

Figure 5.2).

PM_{2.5} Exceedances

Figure 5.2 shows that 5, 3 and 2 exceedances were recorded for PM_{2.5} during the summer, in December, January and February, respectively, when compared to the WHO, and none when compared to the NAAQS. In autumn, the station recorded 4 exceedances in March, when compared to the WHO, and no exceedances were recorded, when compared to the NAAQS, while there were six exceedances in April, when compared to the WHO, and none, when compared to NAAQS, and 22 and 4 exceedances were recorded in May, when compared to the WHO and NAAQS, respectively. In winter (June), the station recorded 22 and 13 exceedances, compared to the WHO and NAAQS, respectively. In July, there were 22 and 14 exceedances, when compared with the WHO and NAAQS, respectively. In August, the station

recorded 6 and 15 when compared to the NAAQS and WHO thresholds, respectively. In spring (September), the station recorded 7 and 1 exceedance compared to the WHO and NAAQS, respectively. In October, 10 exceedances were recorded when compared to the WHO, and no exceedances were recorded, when compared to the NAAQS, while in November, 2 exceedances were recorded when compared to the WHO, and no exceedances were recorded when compared to NAAQS.

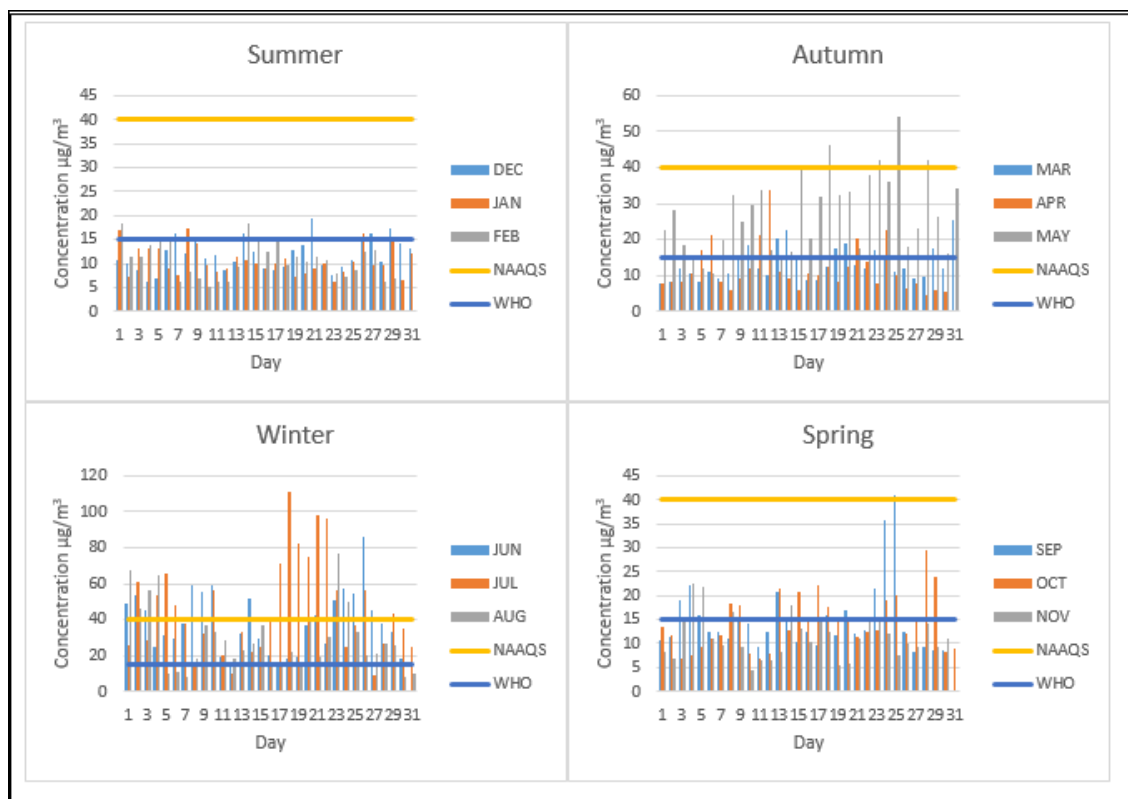


Figure 5.2 Settlers PM_{2.5} 24-hour average concentration

5.2.1.3 Ganges

PM_{2.5} concentrations

The Ganges air quality monitoring station recorded an overall highest peak of 90,73204167µg/m³ in July 2020 (refer to Figure 5.3).

PM_{2.5} Exceedances

Figure 5.3 shows that a total of 12 and 2 exceedances were recorded in December and February, respectively, when compared with the WHO, and no exceedances were observed compared to the NAAQS. In autumn, 5 exceedances were observed in April compared to the WHO, no exceedances were recorded when compared to NAAQS, while 21 and 1 exceedances were observed in May, when compared with the WHO and NAAQS, respectively. In winter (June), the station recorded 17 and 10 exceedances when

compared to the WHO and NAAQS, respectively. In July, there were 20 and 11 exceedances when compared with the WHO and NAAQS, respectively. In August, the station recorded 14 and 7 when compared to the WHO and NAAQS thresholds, respectively. In spring the station recorded 1 and 4 exceedances in September compared to WHO and NAAQS, respectively, and in October, 6 exceedances were recorded when compared to the WHO, and no exceedances compared to the NAAQS. In November, 8 exceedances were recorded when compared to the WHO, and no exceedances were recorded when compared to the NAAQS.

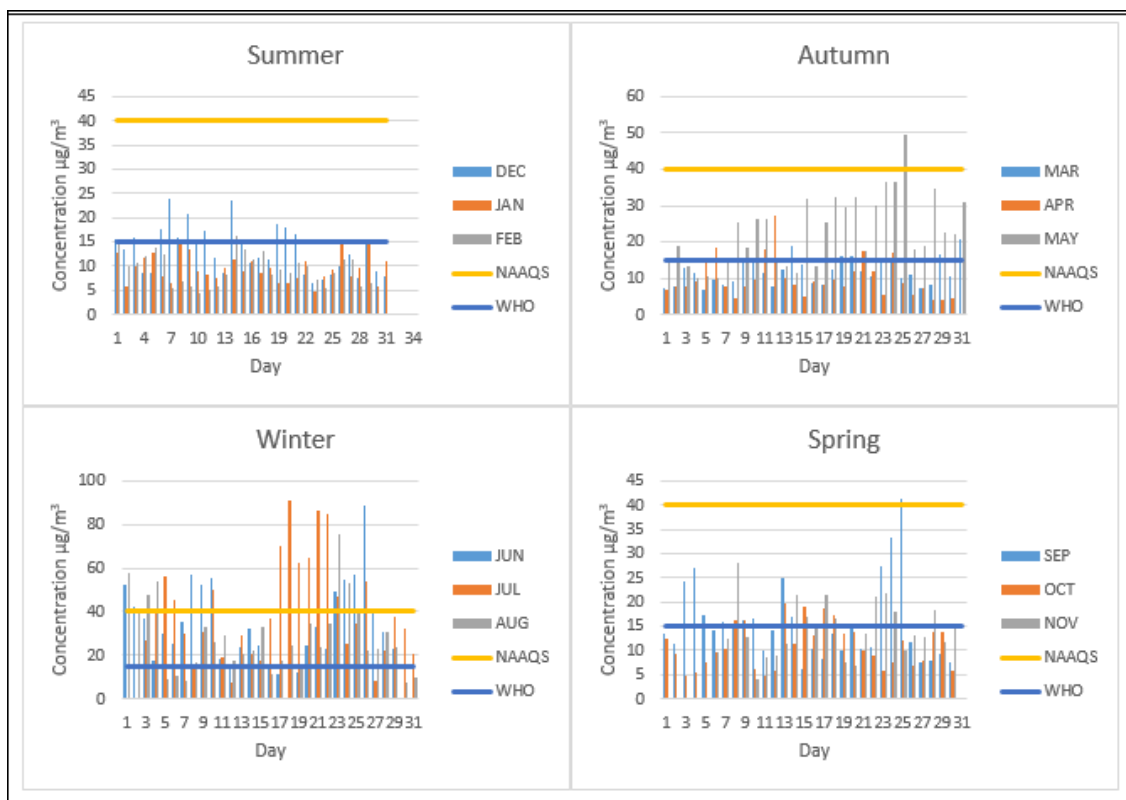


Figure 5.3 Ganges PM_{2.5} 24-hour average concentration

5.2.1.4 Pietermaritzburg Airport

PM_{2.5} concentrations

The Pietermaritzburg Airport air quality monitoring station recorded an overall highest peak of 259,774875 µg/m³ in January 2020 for PM_{2.5} (refer to Figure 5.4).

PM_{2.5} Exceedances

Figure 5.4 shows that the station recorded two exceedances in summer (January), when compared to both the WHO and NAAQS, and the station also recorded two exceedances in February when

compared to the WHO. while no exceedances were recorded when compared to the NAAQS. In autumn, the station did not record any exceedances when compared to both the NAAQS and WHO, as there were missing data for some months during this season. No data were found in the dataset used for this study for the winter and spring seasons.

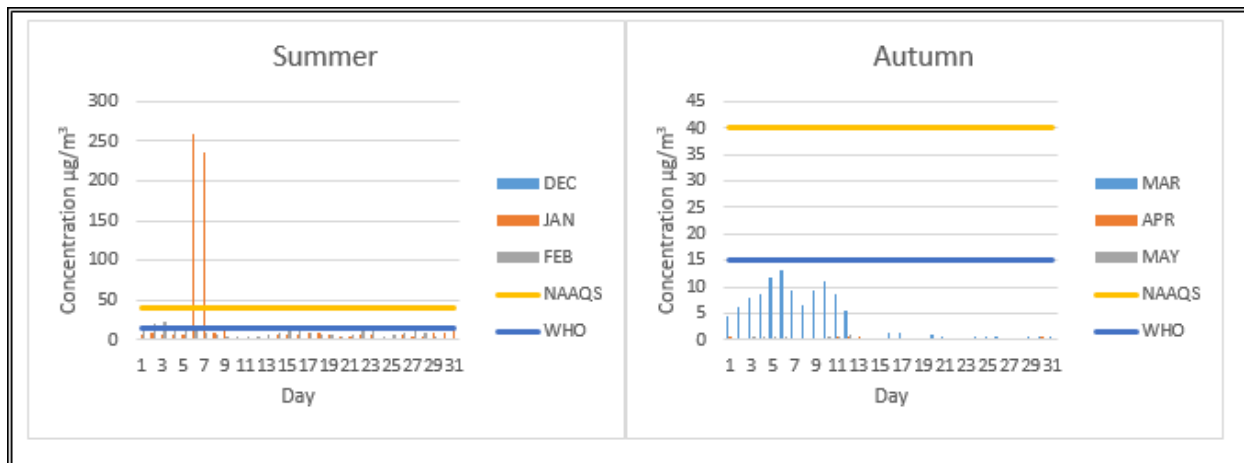


Figure 5.4 Pietermaritzburg Airport PM_{2.5} 24-hour average concentration

5.2.1.5 City Hall

PM₁₀ concentrations

The City Hall air-monitoring station recorded an overall highest peak of 135.673 µg/m³ in July 2020 (refer to Figure 5.5 below).

PM₁₀ exceedances

Figure 5.5 shows that City Hall station recorded 1 exceedance during the summer season (January) when compared to the WHO, and no exceedances when compared to the NAAQS. In autumn, the station recorded 8 exceedances according to the WHO guidelines in May, and when compared to the NAAQS, there were no exceedances during this season. In winter (June), the station recorded 7 and 4 exceedances, compared to the WHO and NAAQS, respectively. In July, there were 18 and 10 exceedances, respectively, when compared with WHO and NAAQS. In August, the station recorded 10 and 3, respectively, when compared to the WHO and NAAQS. In spring (September), the station recorded 3 and 1 exceedance, respectively, when compared to the WHO and NAAQS. In October, 5 exceedances were recorded when compared to the WHO, while no exceedances were recorded when compared to the NAAQS, and in November, no exceedances were recorded when compared to both the WHO and NAAQS.



Figure 5.5 City Hall PM₁₀ 24-hour average concentration

5.2.1.6 Settlers

PM₁₀ concentrations

The Settlers air monitoring station recorded an overall highest peak of 157,148 µg/m³ in July 2020 (refer to Figure 5.6 below).

PM₁₀ exceedances

Figure 5.6 shows that the station recorded 2 exceedances in February when compared to the WHO as a threshold, and no exceedances were recorded when compared to the NAAQS during the summer season. In autumn, the station recorded 4 and 2 exceedances in March and April, respectively, compared to the WHO, and no exceedances were recorded when compared to the NAAQS. Sixteen (16) and four (4) exceedances were recorded according to the WHO and NAAQS, respectively, in May. In winter (June), the station recorded 23 and 11 exceedances when compared to the WHO and NAAQS, respectively. In July, 24 and 13 exceedances were recorded compared with the WHO and NAAQS, respectively. In August, the station recorded 19 and 8 exceedances when compared to the WHO and NAAQS, respectively. In spring (September), the station recorded 4 and 2 exceedances when compared to the WHO and NAAQS. In October, 6 exceedances were recorded when compared to the WHO, and no exceedances were recorded

when compared to the NAAQS, while 1 exceedance was recorded in November compared to the WHO and no exceedances were recorded when compared to the NAAQS threshold.

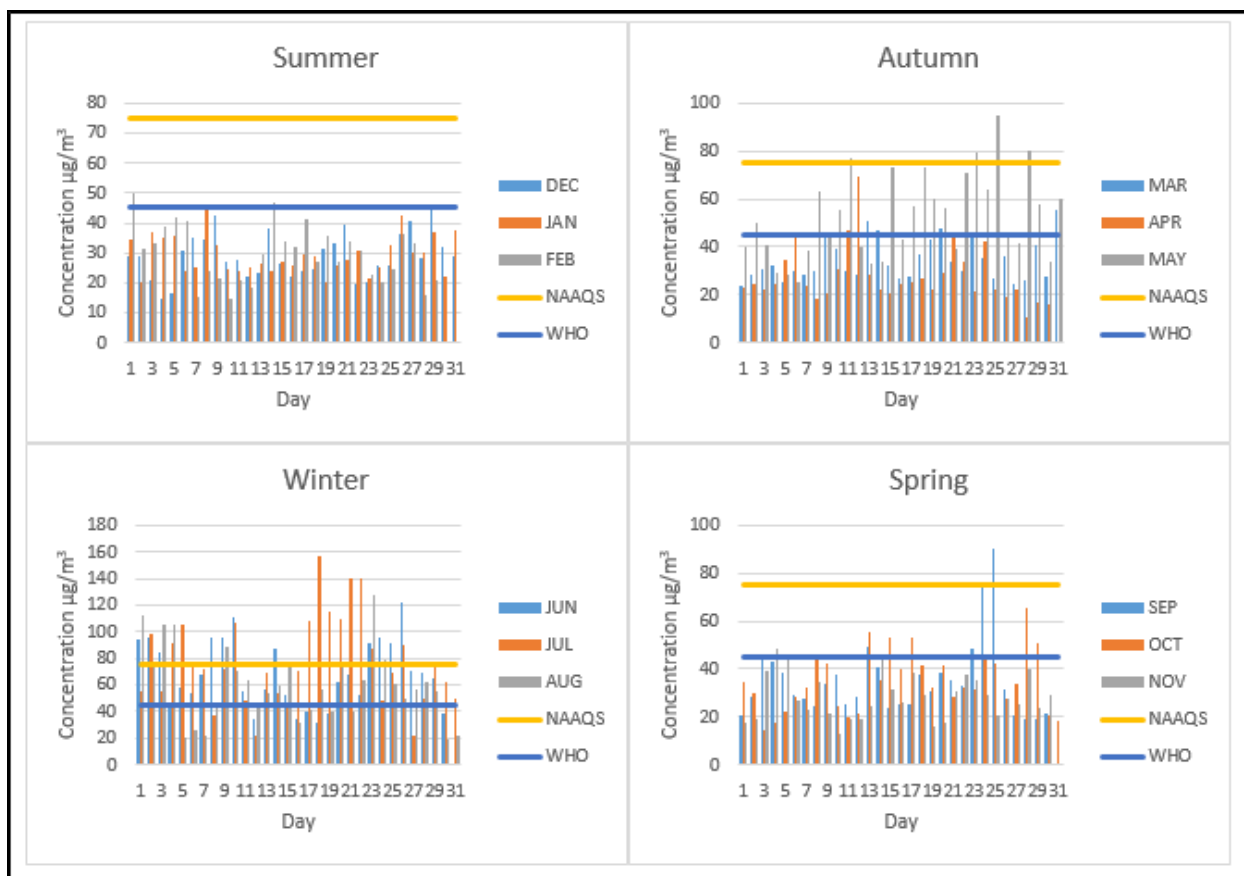


Figure 5.6 Settlers PM₁₀ 24-hour average concentration

5.2.1.7 Ganges

PM₁₀ concentrations

The Ganges air monitoring station recorded an overall highest peak of 135,103µg/m³ in June 2020 (refer to Figure 5.7 below).

PM₁₀ exceedances

Figure 5.7 shows that the station recorded 3 exceedances in December compared to the WHO and no exceedances were observed compared to the NAAQS during the summer. In autumn, the station recorded only one exceedance in April compared to the WHO, while no exceedances were recorded when compared to the NAAQS, and in May, 16 and 3 were recorded when compared with the WHO and NAAQS, respectively. In winter (June), the station recorded 22 and 10 exceedances when compared to the WHO and NAAQS, respectively. In July, there were 21 and 11 exceedances compared with WHO and NAAQS,

respectively. In August, the station recorded 22 and 6 exceedances, compared to the WHO and NAAQS, respectively. In spring (September) the station recorded 6 (six) and 1 (one) exceedances when compared to the WHO and NAAQS, respectively. In October 2 (two) exceedances were observed compared to the WHO, and no exceedances were recorded when compared to the NAAQS. In November, 5 (five) exceedances were recorded when compared to the WHO, while no exceedances were recorded when compared to the NAAQS.

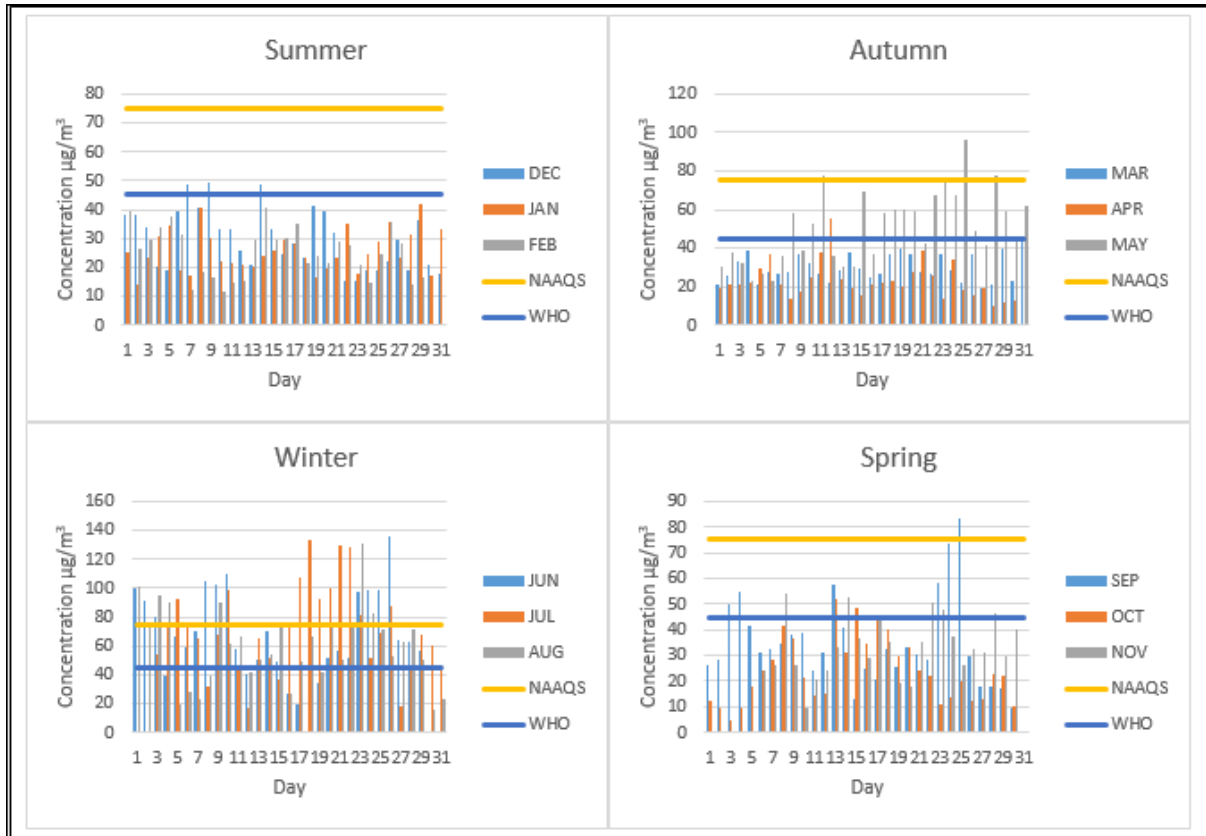


Figure 5.7 Ganges PM₁₀ 24-hour concentration

5.2.1.7 Pietermaritzburg Airport

PM₁₀ concentrations

The Pietermaritzburg Airport air monitoring station recorded an overall highest peak of 64,417µg/m³ in May and June 2020 (refer to Figure 5.8 below).

PM₁₀ exceedances

Figure 5.8 shows that the station recorded no exceedances in summer for PM₁₀ when compared to NAAQS and WHO thresholds. In autumn (May), the station recorded 12 exceedances compared to the WHO, and no exceedances according to the NAAQS guidelines. In winter (June and July), the station recorded 27 and 31 exceedances, respectively, when compared to the WHO and no exceedances were recorded when

compared to the NAAQS. In August, the station recorded 25 exceedances when compared to WHO threshold, and no exceedances when compared to the NAAQS. No data was recorded during the spring season.

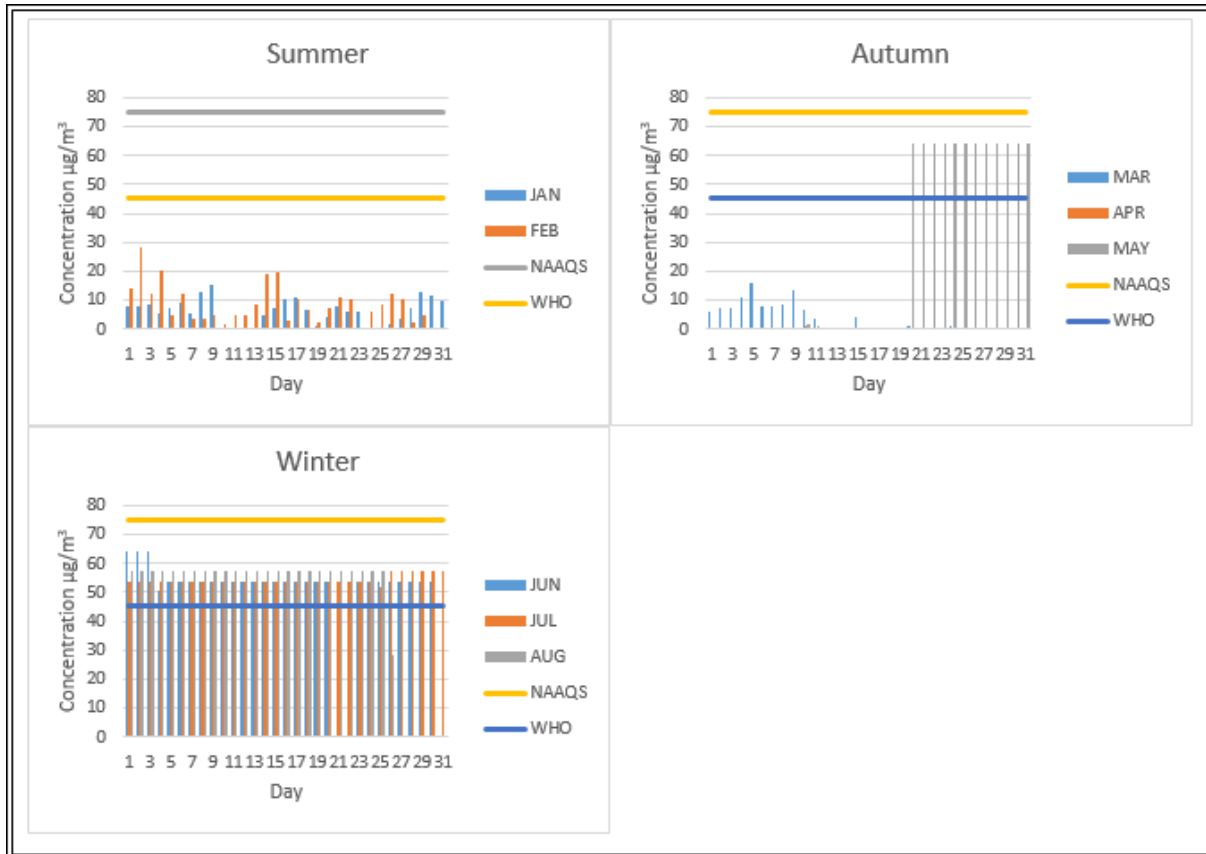


Figure 5.8 Pietermaritzburg Airport PM₁₀ 24-hour average concentration

Table 5.1 Summary table of PM2.5 and PM10 pollutants

Station	Pollutant	# of exceedances WHO	# of exceedances NAAQS	Month	Season
City Hall	PM _{2.5}	1	0	January	Summer
		2	0	April	Autumn
		15	0	May	
		14	1	June	Winter
		22	10	July	
		14	2	August	
		5	0	September	Spring
	9	0	October		
	2	2	November		
	PM ₁₀	1	0	January	Summer
		8	0	May	Autumn
		7	4	June	Winter
		18	10	July	
		10	3	August	
3		1	September	Spring	
5		0	October		
Settlers	PM _{2.5}	5	0	December	Summer
		3	0	January	
		2	0	February	
		4	0	March	Autumn
		6	0	April	
		22	4	May	
		22	13	June	Winter
		22	14	July	
		15	6	August	
		7	1	September	Spring
		10	0	October	
		2	0	November	

Station	Pollutant	# of exceedances WHO	# of exceedances NAAQS	Month	Season	
	PM ₁₀	2	0	February	Summer	
		4	2	March	Autumn	
		4	2	April		
		16	4	May		
		23	11	June	Winter	
		24	13	July		
		19	8	August		
		4	2	September	Spring	
		6	0	October		
		1	0	November		
Wentworth	PM _{2.5}	12	0	December	Summer	
		2	0	February		
		5	0	April	Autumn	
		21	1	May		
		17	10	June	Winter	
		20	11	July		
		14	7	August		
		6	0	September	Spring	
	6	0	October			
	8	0	November			
		PM ₁₀	3	0	December	Summer
			1	0	April	Autumn
			16	3	May	
			22	10	June	Winter
21			11	July		
22			6	August		
6			1	September	Spring	
2			0	October		
5	0	November				
Pietermaritzburg Airport	PM _{2.5}	2	2	January	Summer	
		2	0	February		

Station	Pollutant	# of exceedances WHO	# of exceedances NAAQS	Month	Season
	PM ₁₀	12	0	May	Autumn
		27 31 25		June July August	Winter

5.2.1.9 City Hall Station

SO₂ concentrations

The City Hall air quality monitoring station recorded an overall highest peak of 7.78 ppb in June 2020 (refer to Figure 5.9).

SO₂ exceedances

Figure 5.9 shows that no exceedances were recorded as thresholds during the summer, autumn and winter seasons, when compared to the NAAQS and WHO.

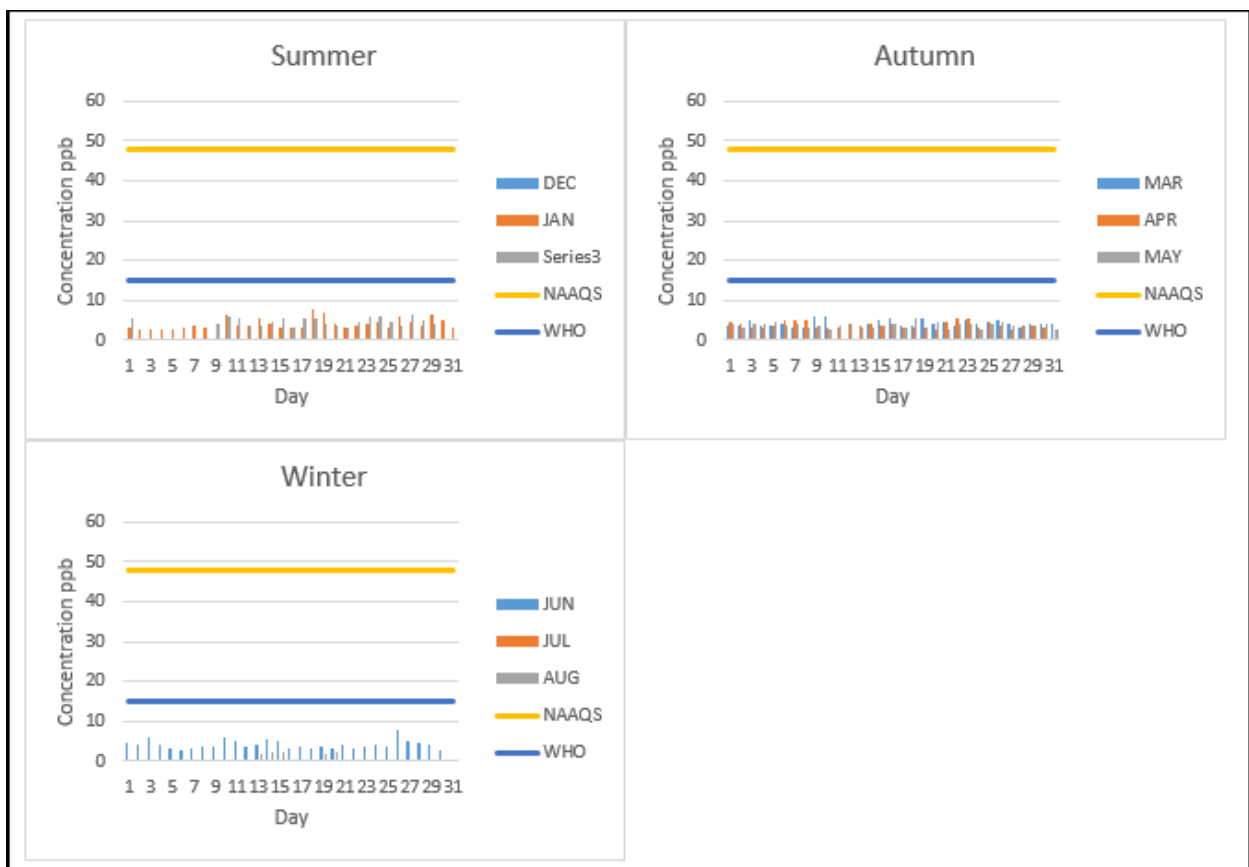


Figure 5.9 City Hall SO₂ 24-hour average concentration

5.2.1.10 Settlers

SO₂ concentrations

The Settlers air-quality monitoring station recorded an overall highest peak of 41.1 ppb in January 2020 (refer to Figure 5.10).

SO₂ exceedances

Figure 5.10 shows that in summer (January and February) settlers station recorded 5 and 4 exceedances, respectively, according to the WHO guidelines, and no exceedances were recorded when compared to the NAAQS. In autumn (March and May), the station recorded 5 and 1 exceedance, respectively, according to the WHO guidelines. In winter (June, July and August), the station recorded 5, 7 and 11 exceedances, respectively, when compared to the WHO, while no exceedances were recorded according to the NAAQS., The station recorded 9, 11 and 15 in the spring (September, October and November, respectively) when compared to WHO, and none of the months exceeded the NAAQS threshold.

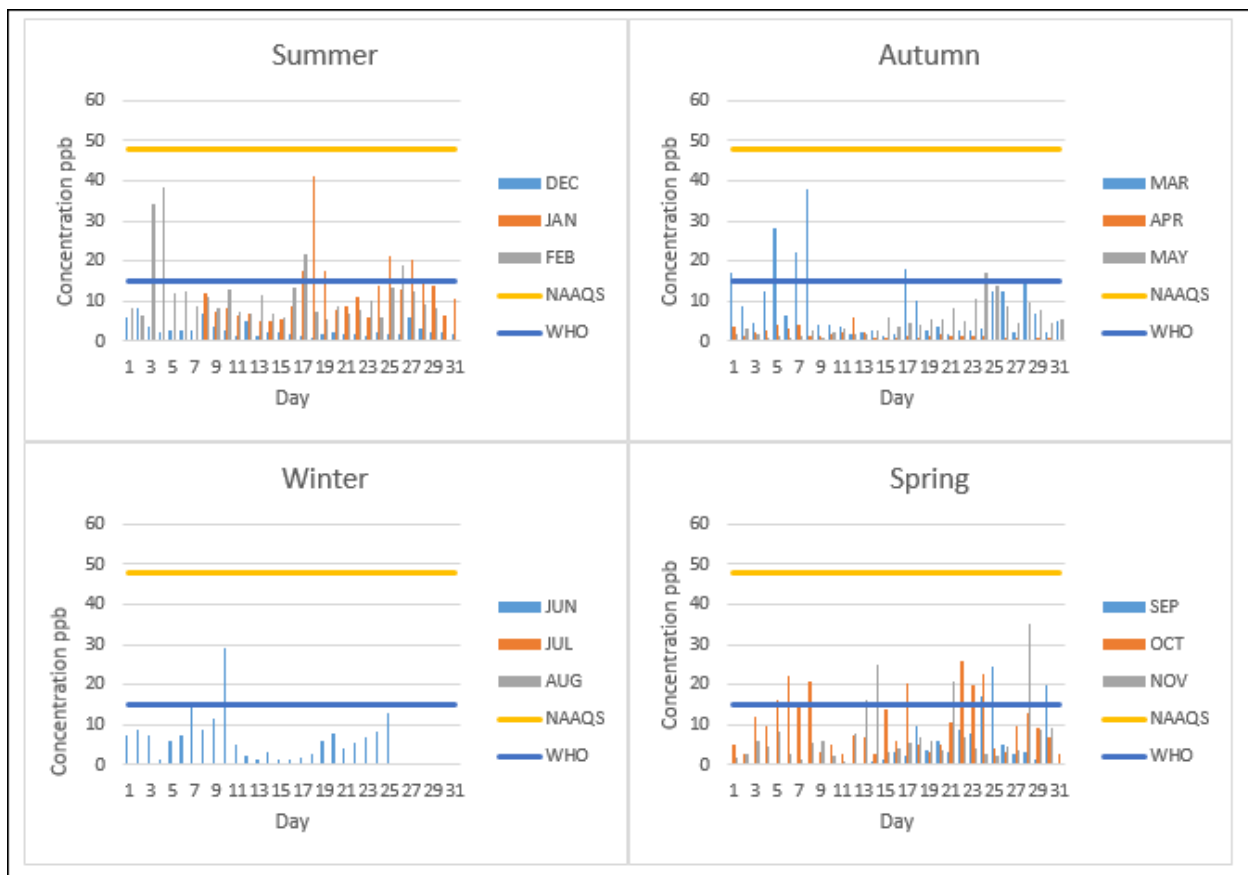


Figure 5.10 Settlers SO₂ 24-hour average concentration

SO₂ concentrations

The Ganges air quality monitoring station recorded an overall highest peak of 24.46 ppb in October 2020 (refer to Figure 5.11).

SO₂ exceedances

Figure 5.11 shows that in summer (January and December) Wentworth station recorded 1 exceedance compared to the WHO, and no exceedances were recorded when compared to NAAQS. In autumn, no exceedances were observed compared to the WHO and NAAQS. In winter, 2 and 3 exceedances were observed in June and August, respectively, compared to the WHO, and there were no exceedances compared to the NAAQS. In spring, the station recorded 1, 4 and 5 exceedances for the months of September, October and November, respectively, compared to WHO, and there were no exceedances when compared to NAAQS.

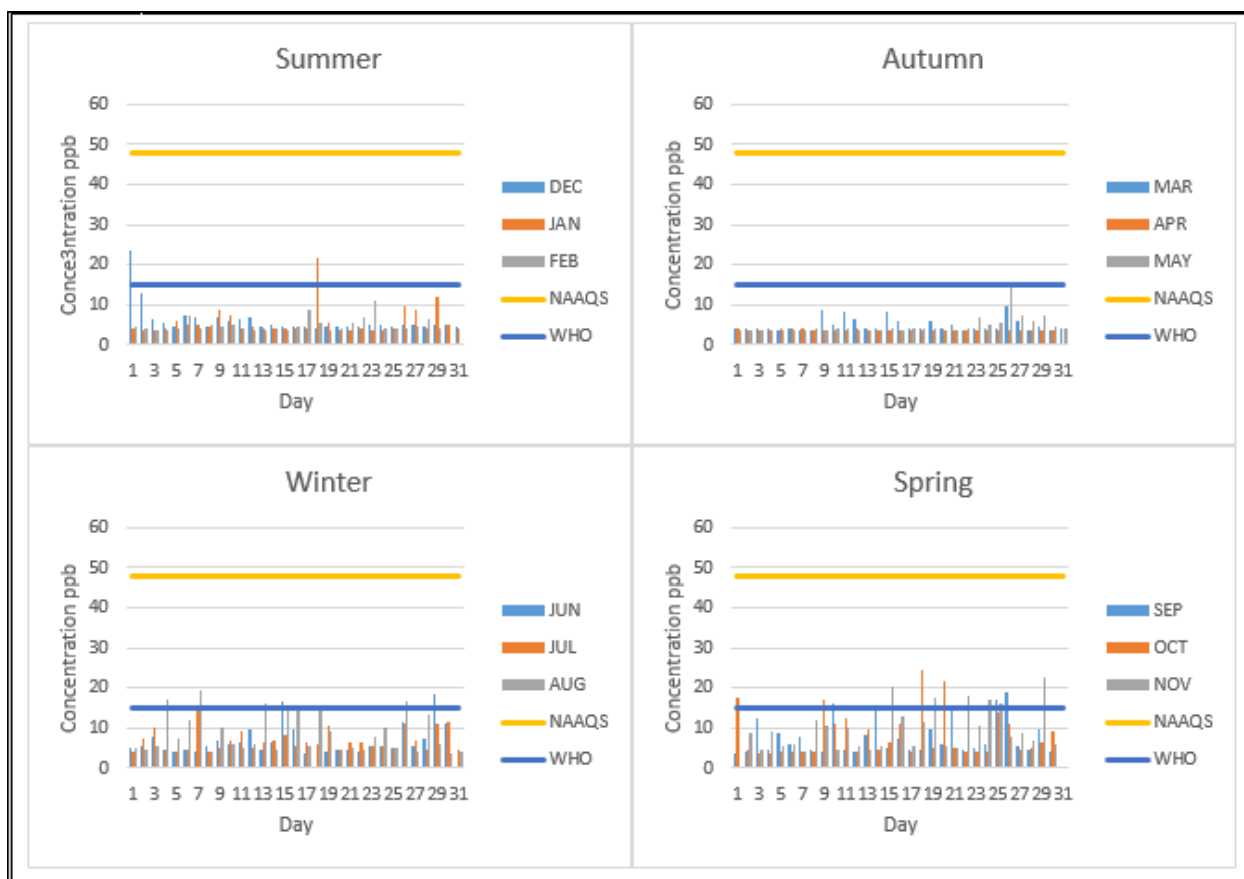


Figure 5.11 Ganges SO₂ 24-hour average concentration

SO₂ concentrations

The Amanzimtoti air quality monitoring station recorded an overall highest peak of 116.57 ppb in July 2020 (refer to Figure 5.12).

SO₂ exceedances

Figure 5.12 shows that the Amanzimtoti station recorded no exceedances in the summer, autumn and spring, when compared with the NAAQS and WHO. In winter (June), the station recorded no exceedances when compared to the WHO and NAAQS, while in July, 8 (eight) and 6 (six) exceedances were recorded when compared to the WHO and NAAQS, respectively. Lastly, the station recorded 6 exceedances in July when compared to the NAAQS, and no exceedances were recorded in August, compared to the NAAQS and WHO.

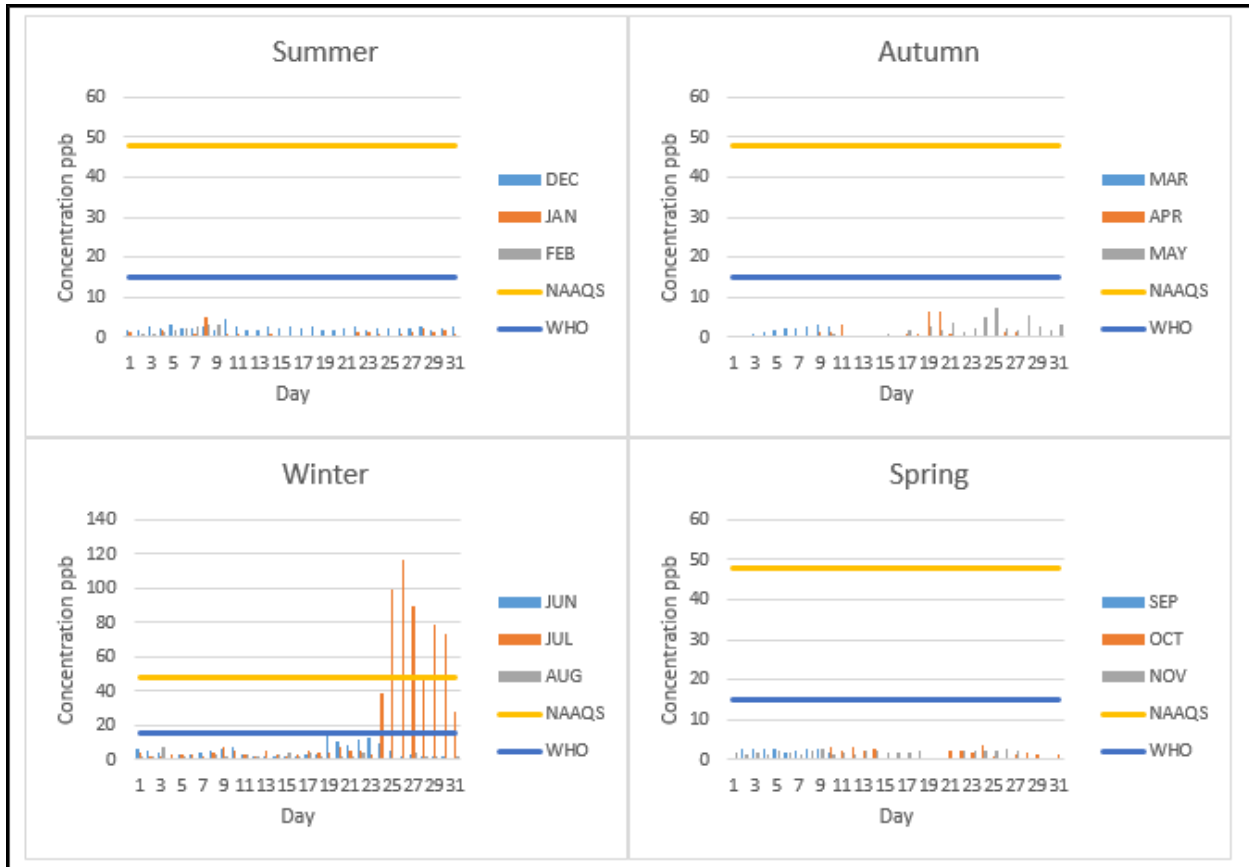


Figure 5.12 Amanzimtoti SO₂ 24-hour average concentration

5.2.1.13 Ganges Station

SO₂ concentrations

The Ganges air-monitoring station recorded an overall highest peak of 14.08 ppb in July 2020 (refer to Figure 5.13).

SO₂ exceedances

The Ganges monitoring station did not record any exceedances in all the seasons, when compared to the NAAQS and WHO thresholds (refer to Figure 5.13).

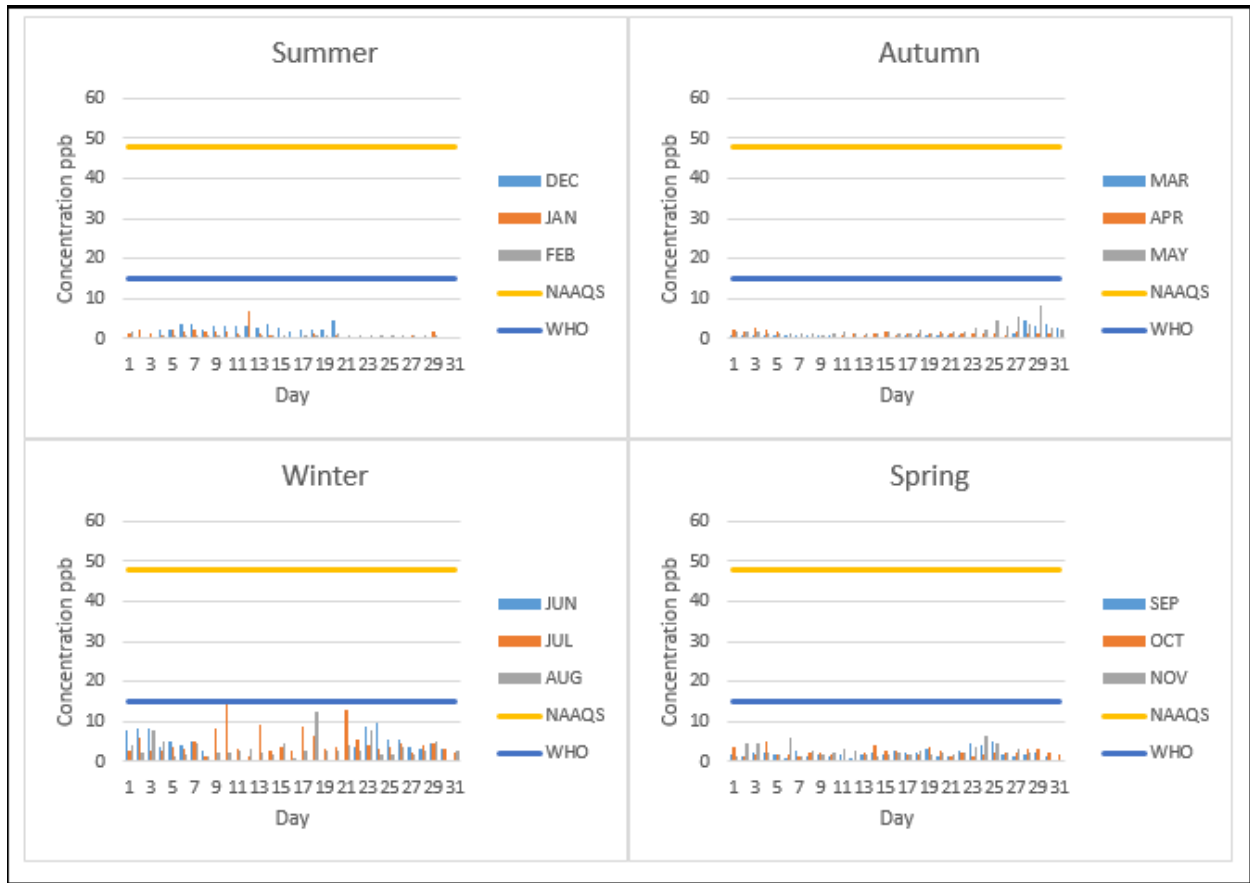


Figure 5.13 Ganges SO₂ 24-hour average concentration

5.2.1.14 Edendale Station

SO₂ concentrations

The Edendale air monitoring station recorded an overall highest peak of 36.18 ppb in July 2020 (refer to Figure 5.14)

SO₂ exceedances

The Edendale station recorded 26 exceedances in December, 10 exceedances in January and 23 exceedances in December compared to the WHO guidelines, and no exceedances were recorded during the summer season when compared to the NAAQS. In autumn, winter and spring there were no exceedances when compared to the WHO and NAAQS (refer to Figure 5.14).

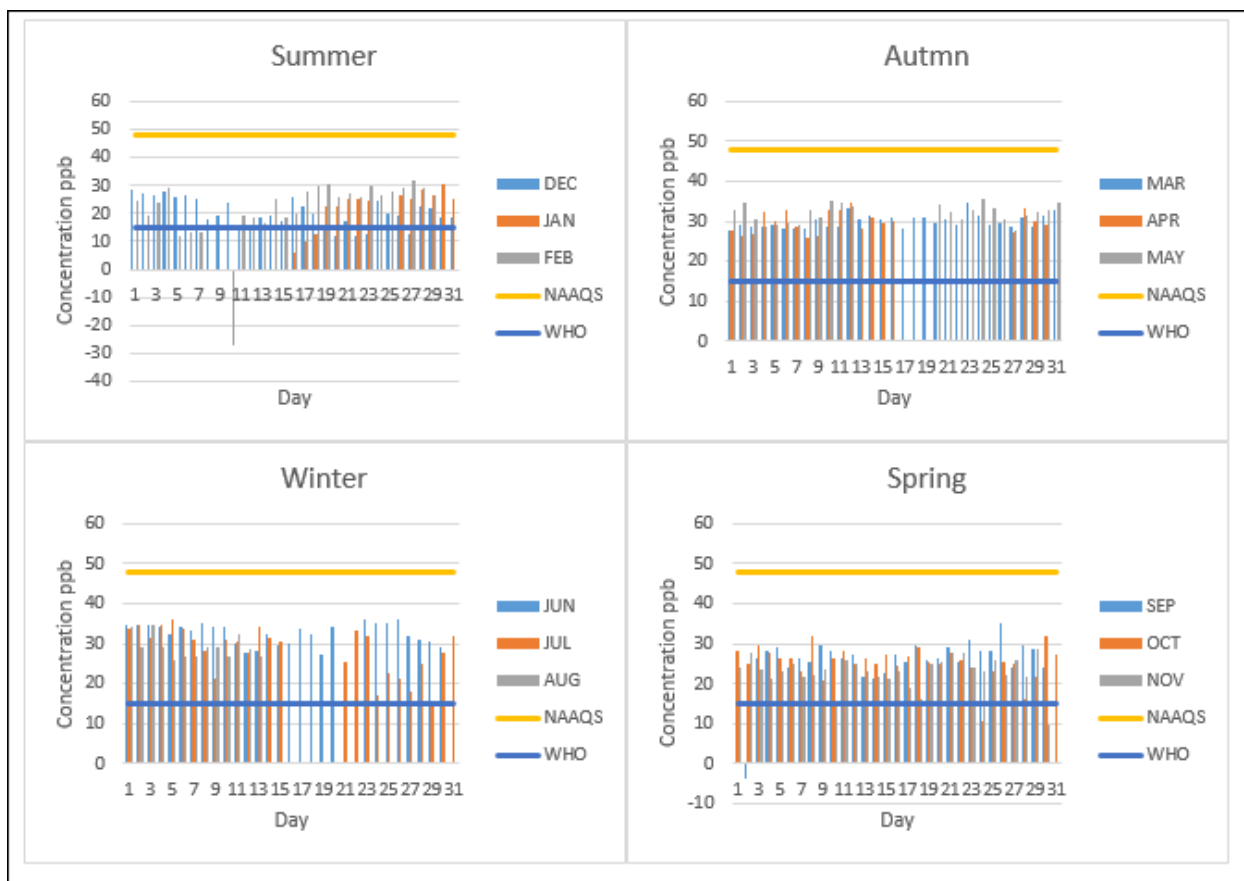


Figure 5.14 Edendale SO₂ 24-hour average concentration

5.2.1.15 Pietermaritzburg Airport Station

SO₂ concentrations

The Pietermaritzburg Airport air monitoring station recorded an overall highest peak of 33.30 ppb in September 2020 (refer to Figure 5.15).

SO₂ exceedances

Figure 5.15 shows that Pietermaritzburg Airport station reported no exceedances in summer (January and February) when compared to the NAAQS and WHO, while 17 exceedances were recorded in December when compared to the NAAQS and WHO. In autumn the station recorded 1 (one) exceedance when compared to WHO, while no exceedances were recorded when compared to NAAQS in March; furthermore, no exceedances were observed in April and May. In winter (June and August) the station did not record any exceedances when compared to the WHO and NAAQS, with only 1 exceedance in July when compared to the WHO, and no exceedances when compared with the NAAQS. In spring (September), the station recorded 7 exceedances compared to the WHO, while 4 exceedances were recorded in October, compared to the WHO. In November, 7 exceedances were recorded compared to the WHO and the station did not record any SO₂ concentrations that exceeded the NAAQS threshold during this period.

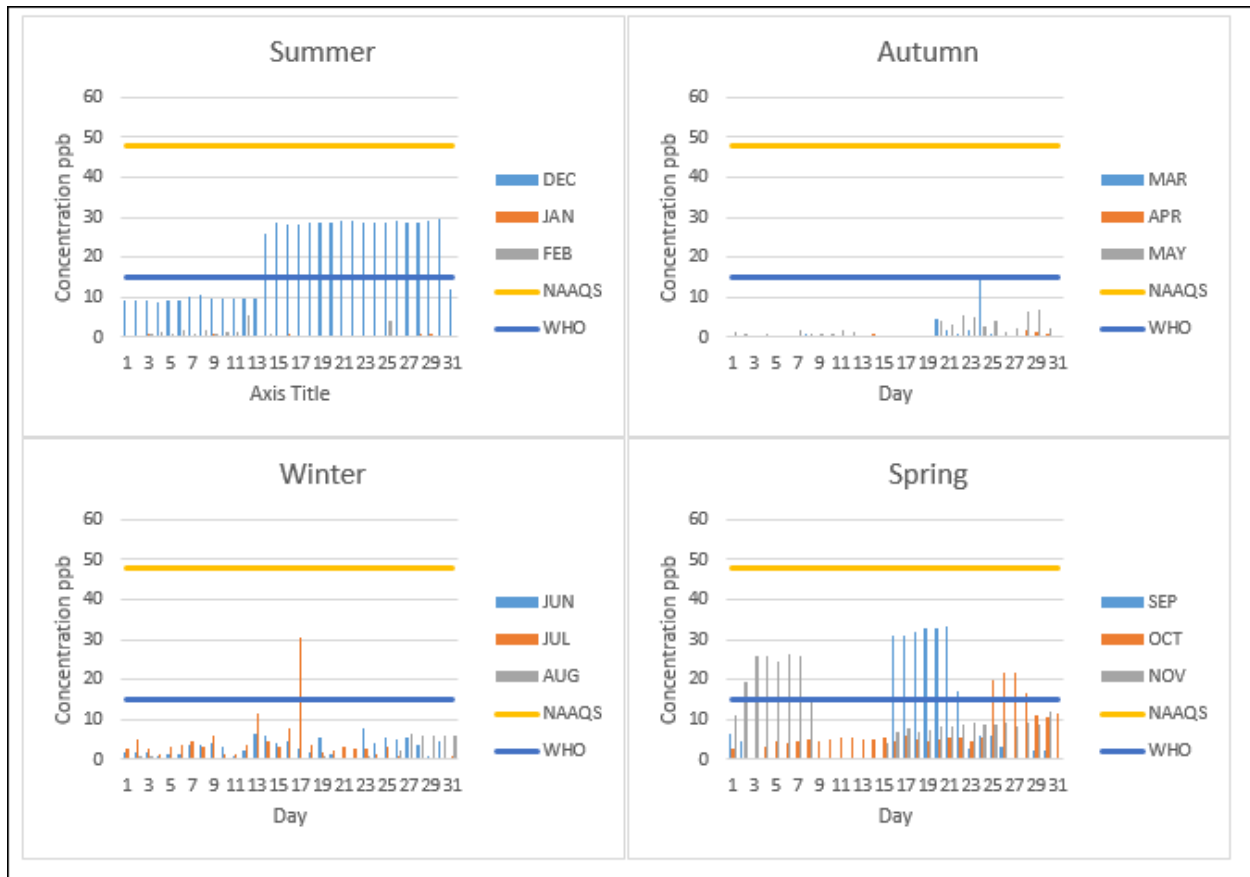


Figure 5.15 Pietermaritzburg Airport SO₂ 24-hour average concentration

5.2.1.16 Pietermaritzburg CBD Station

SO₂ concentrations

The Pietermaritzburg CBD air monitoring station recorded an overall highest peak of 12.53 ppb in June 2020 (refer to Figure 5.16).

SO₂ exceedances

Figure 5.16 shows that the station did not record any exceedances in all the seasons, when compared to the NAAQS and WHO.

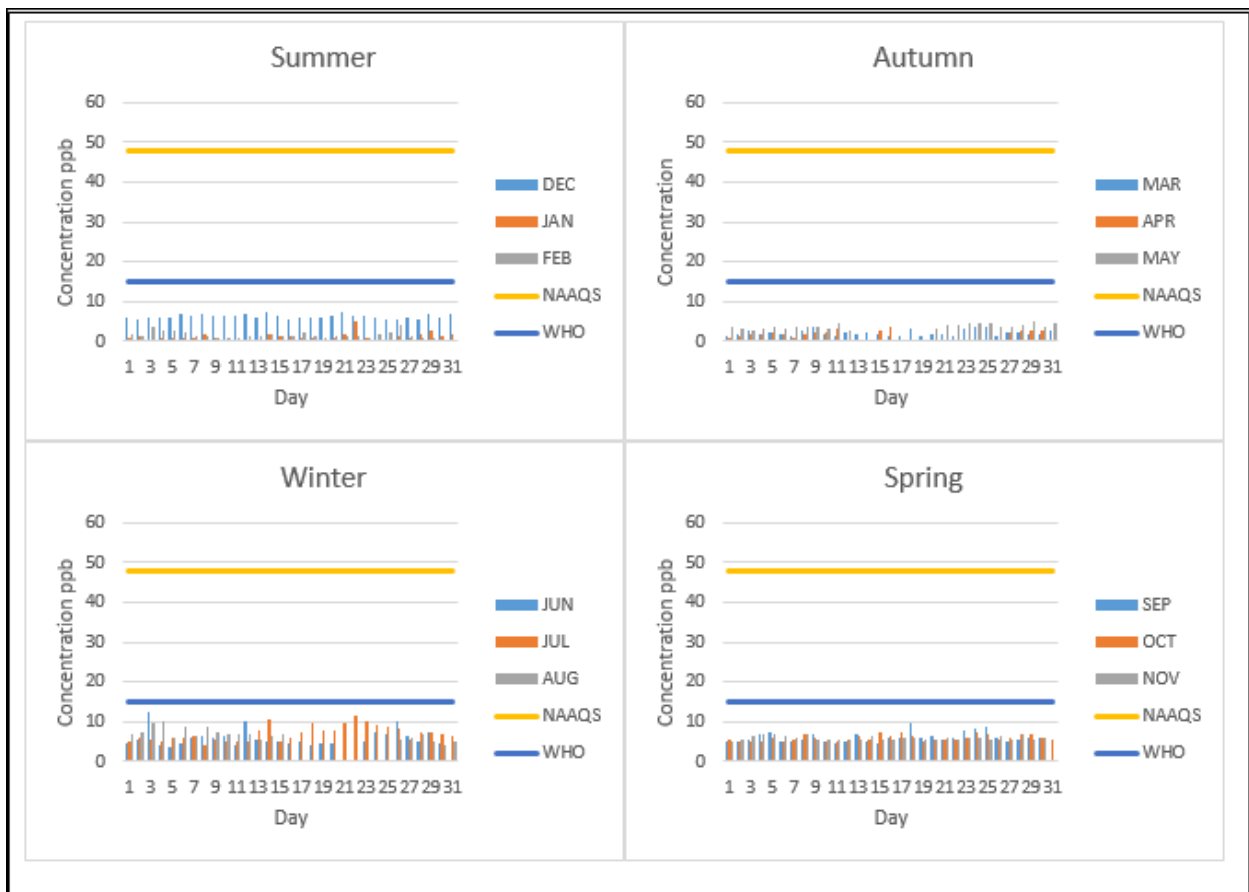


Figure 5.16 Pietermaritzburg CBD SO₂ 24-hour average concentration

5.2.1.17 Ganges Station

NO₂ concentrations

The Ganges air quality monitoring station recorded an overall highest peak of 126.52 ppb in June 2020 (refer to Figure 5.17).

NO₂ exceedances

Figure 5.17 shows that Ganges monitoring station recorded no exceedances in the summer, autumn and spring seasons, when compared to the NAAQS and WHO. In winter, 1 exceedance was recorded in June when compared to both the NAAQS and WHO, and in July, the station recorded two exceedances when compared to the NAAQS and WHO thresholds.

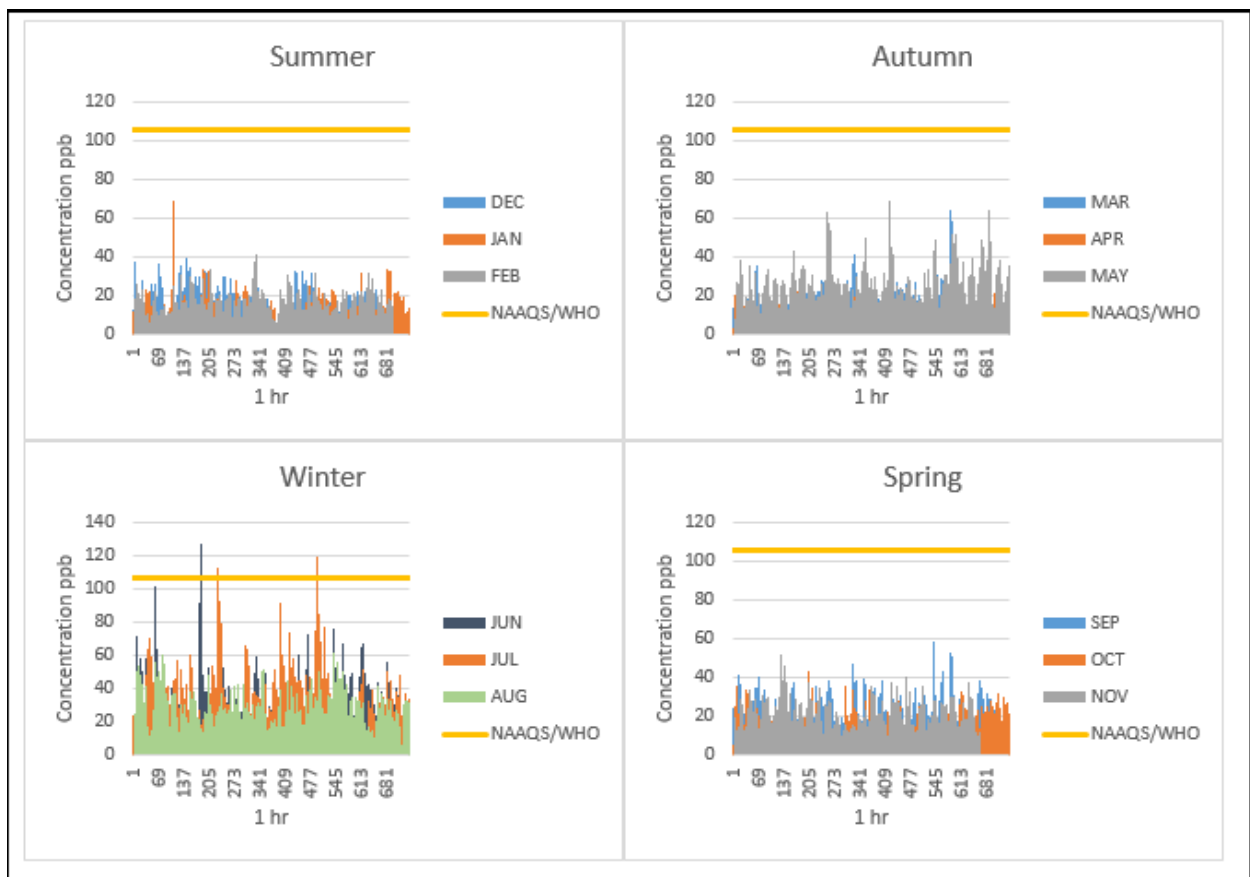


Figure 5.17 Ganges NO₂ 1-hour average concentration

NO₂ concentrations

The Pietermaritzburg CBD air quality monitoring station recorded an overall highest peak of 3061,81ppb in September 2020 (refer to Figure 5.18).

NO₂ exceedances

Figure 5.18 shows that the Pietermaritzburg CBD station recorded no exceedances in summer. In spring (September) there were 53 996 exceedances when compared to both the NAAQS and WHO. No data were recorded for the autumn and winter seasons. Figure 5.18 shows that the Pietermaritzburg Airport station recorded no exceedances in all the seasons when compared to the NAAQS and WHO thresholds.

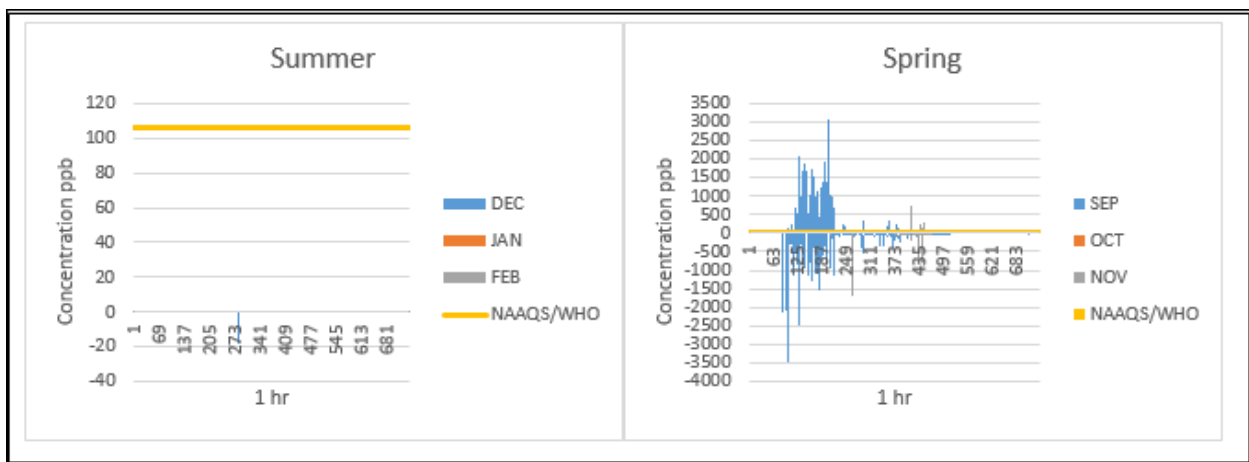


Figure 5.18 Pietermaritzburg CBD NO₂ 1-hour average concentration

5.2.1.19 Pietermaritzburg Airport Station

NO₂ concentrations

The Pietermaritzburg Airport air quality monitoring station recorded an overall highest peak 58 ppb in September 2020 (refer to Figure 5.19).

NO₂ exceedances

Figure 5.19 shows that Pietermaritzburg Airport station recorded no exceedances in all the seasons, when compared to the NAAQS and WHO thresholds.

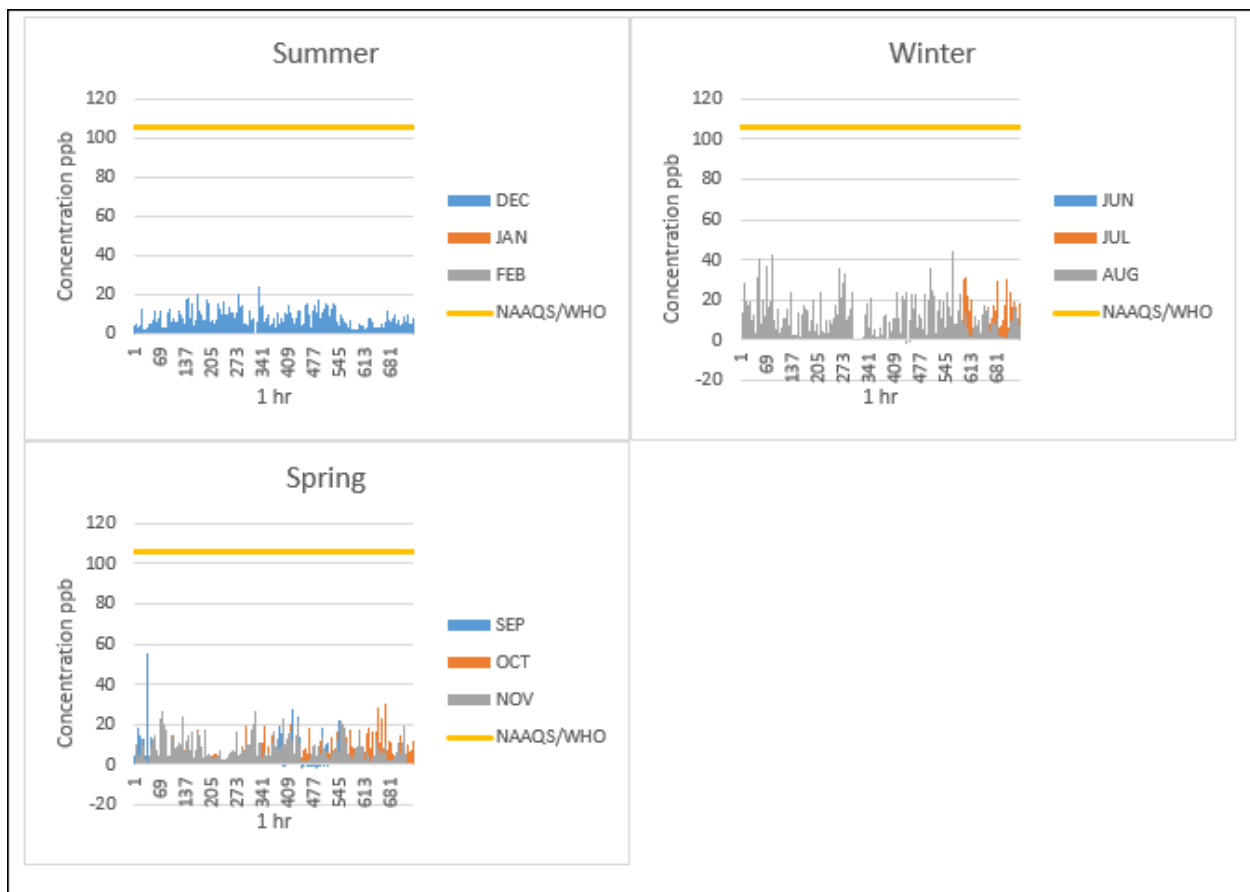


Figure 5.19 Pietermaritzburg Airport NO₂ 1-hour average concentration

5.2.1.20 Hambanathi Station

O₃ Concentrations

The Hambanathi air quality monitoring station recorded an overall highest peak of 47.30ppb in November 2020 (refer to Figure 5.20).

O₃ exceedances

Figure 5.20 shows that the Hambanathi station recorded no exceedances in all the seasons, when compared to the WHO and NAAQS thresholds.

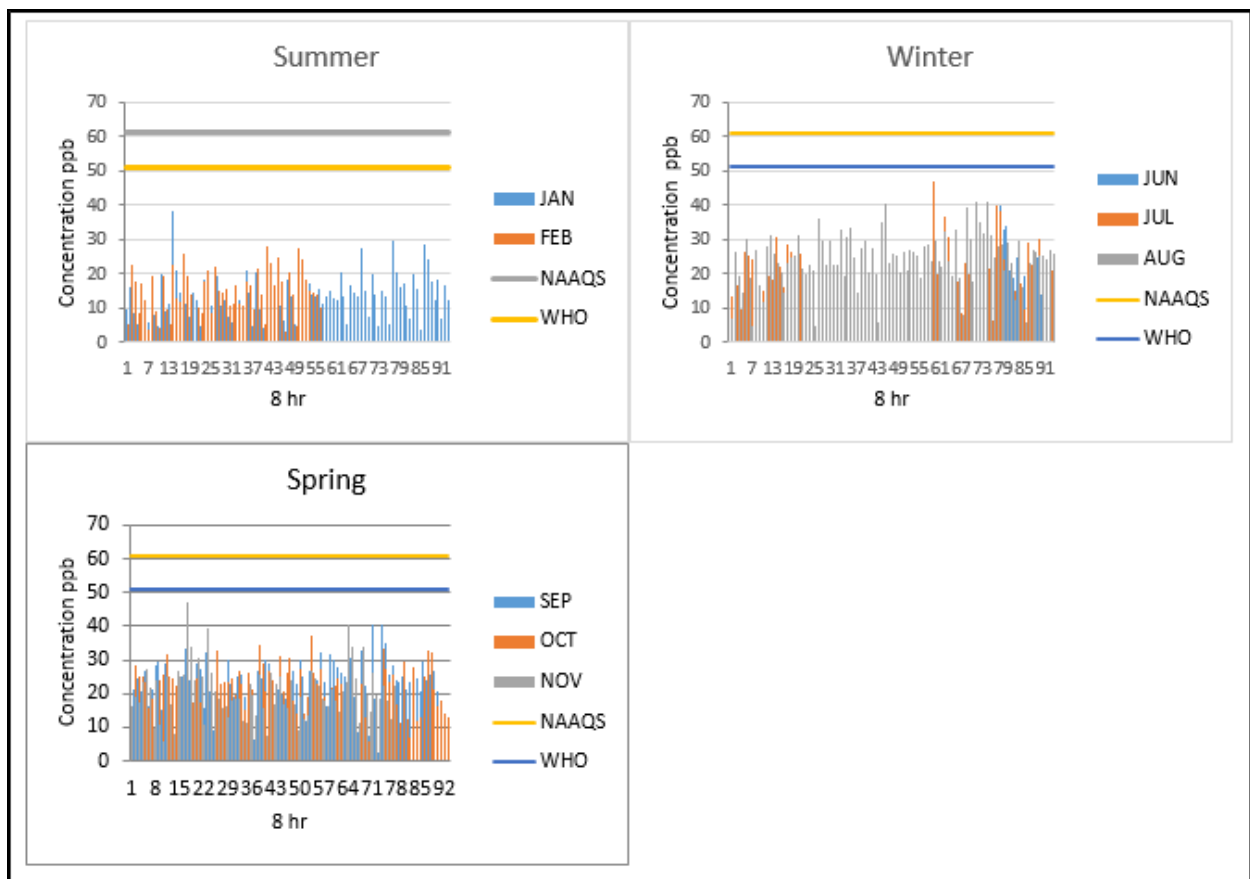


Figure 5.20 Hambanathi O₃ 8-hour average concentration

5.2.1.21 Pietermaritzburg Airport Station

O₃ Concentrations

The Pietermaritzburg Airport air monitoring station recorded an overall highest peak of 4.08 ppb in September 2020 (refer to Figure 5.21).

O₃ exceedances

Figure 5.21 show that Pietermaritzburg Airport station recorded no exceedances in all the seasons, when compared to the WHO and NAAQS thresholds.



Figure 5.21 Pietermaritzburg Airport O₃ 8-hour average concentration

5.2.2 Spatial distribution of air pollutants

5.2.2.1 The eThekweni Municipality

Figure 5.22 shows the spatial distribution of the annual average concentration of PM_{2.5}, PM₁₀, NO₂, SO₂, and O₃ in the eThekweni Municipality. Figure 5.22 demonstrate that the concentration of PM_{2.5} is very high at the Settlers, Ganges and City Hall air monitoring stations. The concentration shows that when the distances increase away from the monitoring station, the PM_{2.5} slowly decreases. Figure 5.23 demonstrate that the highest concentration of PM₁₀ is observed at Settlers and Ganges, and the concentration decreases as the distances increase away from both areas. The SO₂ concentration shows a very high concentration in Settlers and Ganges, while a slight decrease is observed at the Amanzimtoti monitoring station and low values are observed at the City Hall monitoring station. It should be noted that as the distance increases, the concentration of the pollutants decreases, refer to Figure 5.24. The NO₂ concentration is very high at Ganges and Settlers, and it is low at Amanzimtoti and City Hall, while the concentration of NO₂ is observed to decrease with an increase in the distance, refer to Figure 5.25. The O₃ concentration at Hambanathi is observed to be high; however, a decrease in concentration is observed as the distance increases, refer to Figure 5.26.

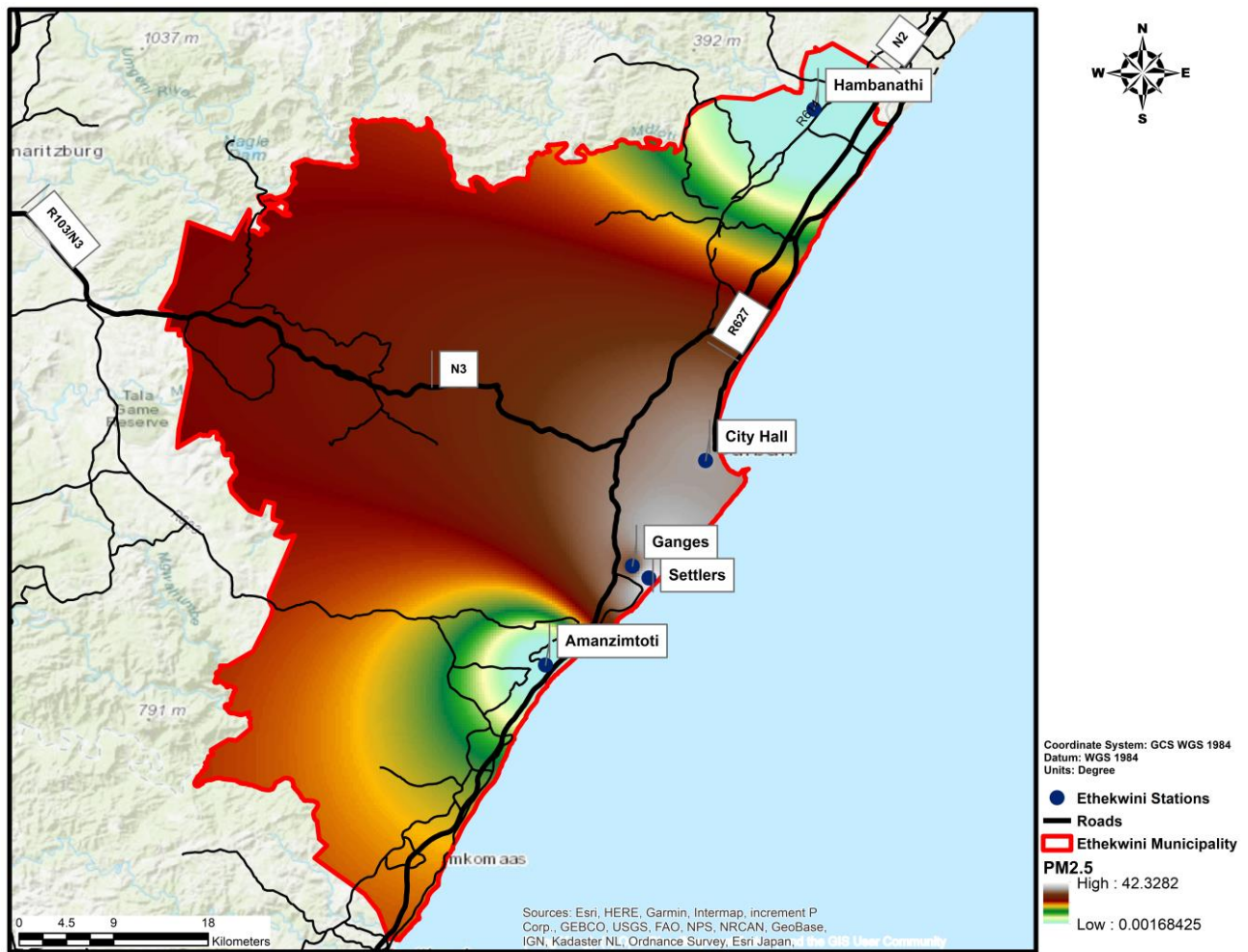


Figure 5.22 Spatial distribution of PM_{2.5} at the eThekweni Municipality

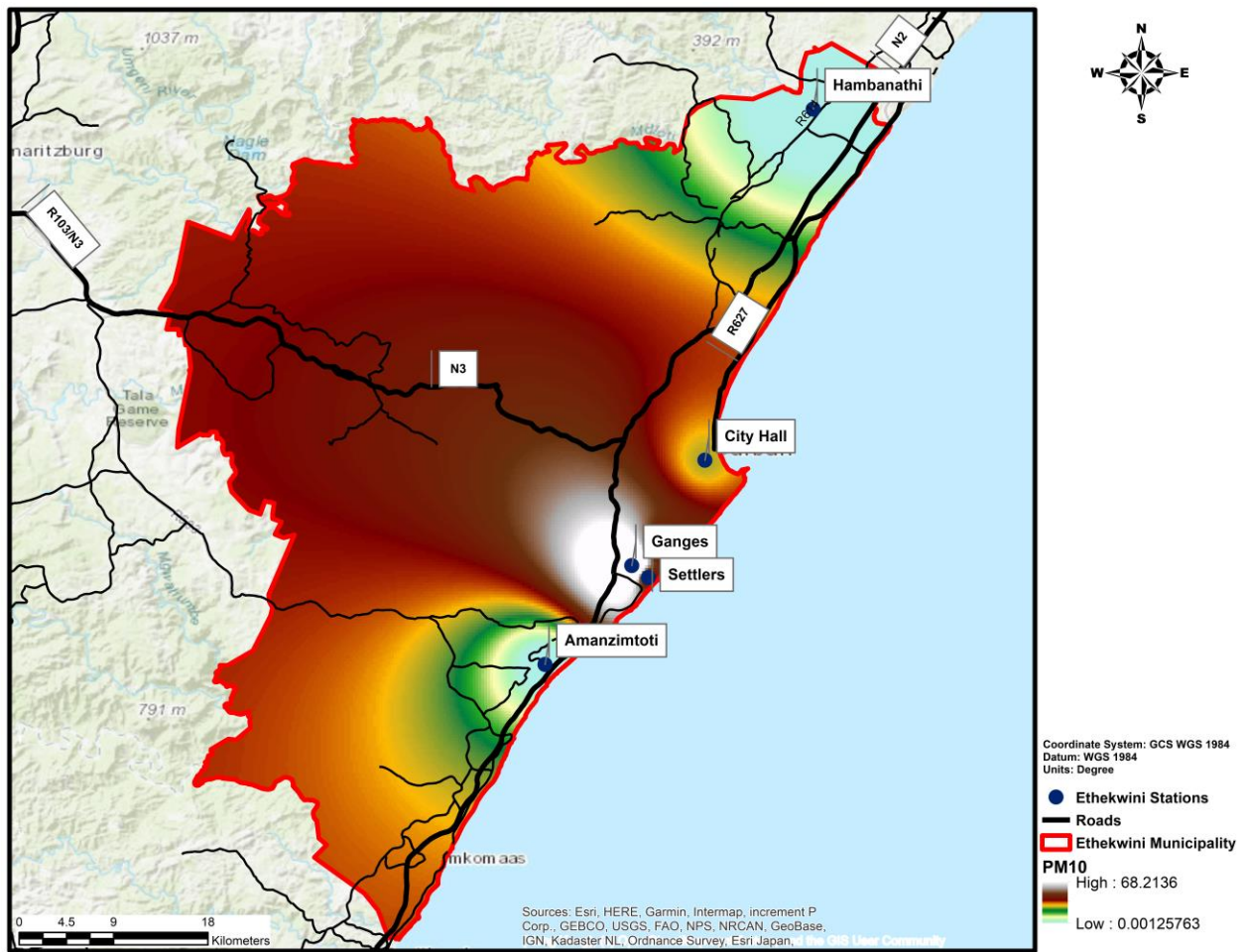


Figure 5.23 Spatial distribution of PM₁₀ at the eThekweni Municipality

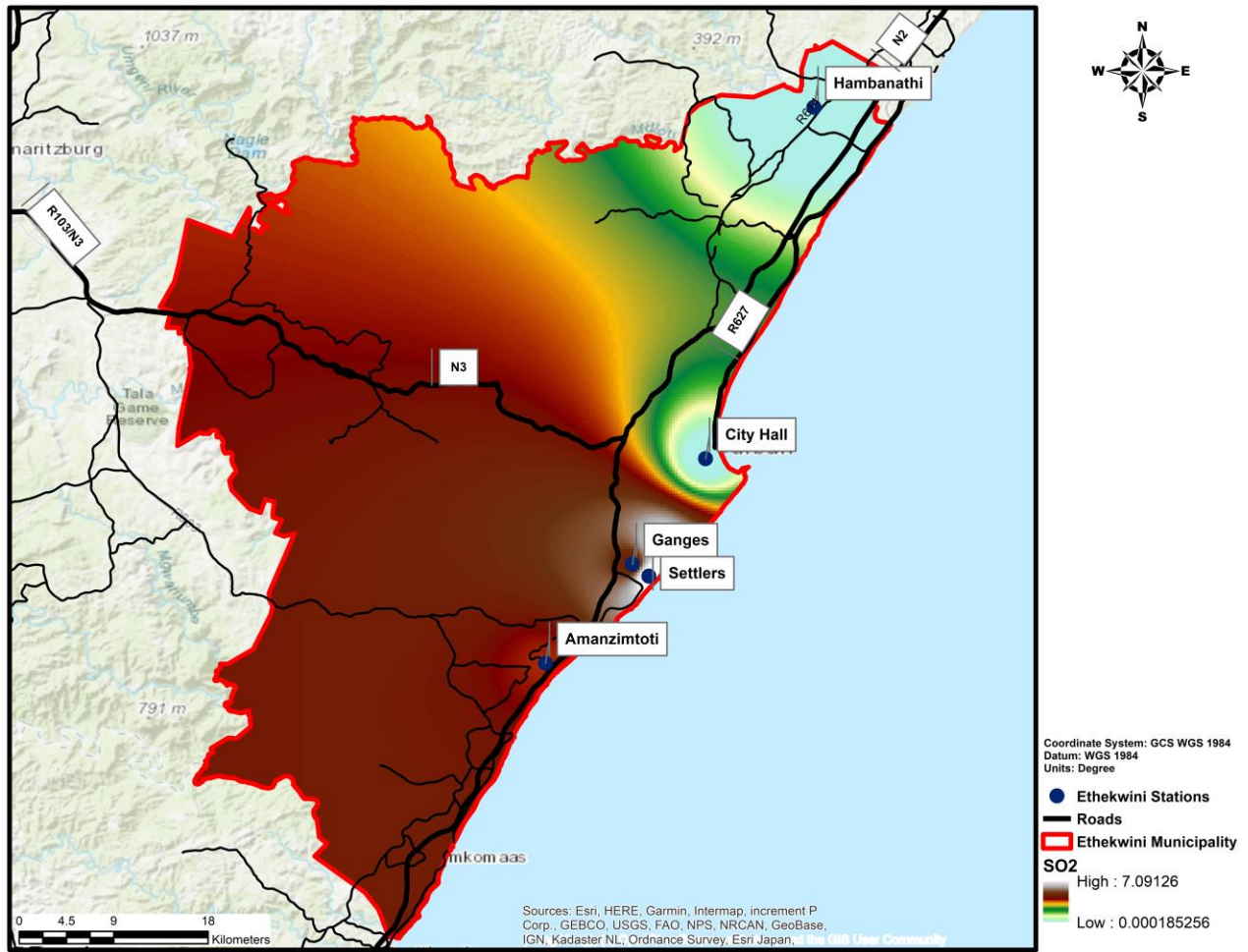


Figure 5.24 Spatial distribution of SO₂ at the eThekweni Municipality

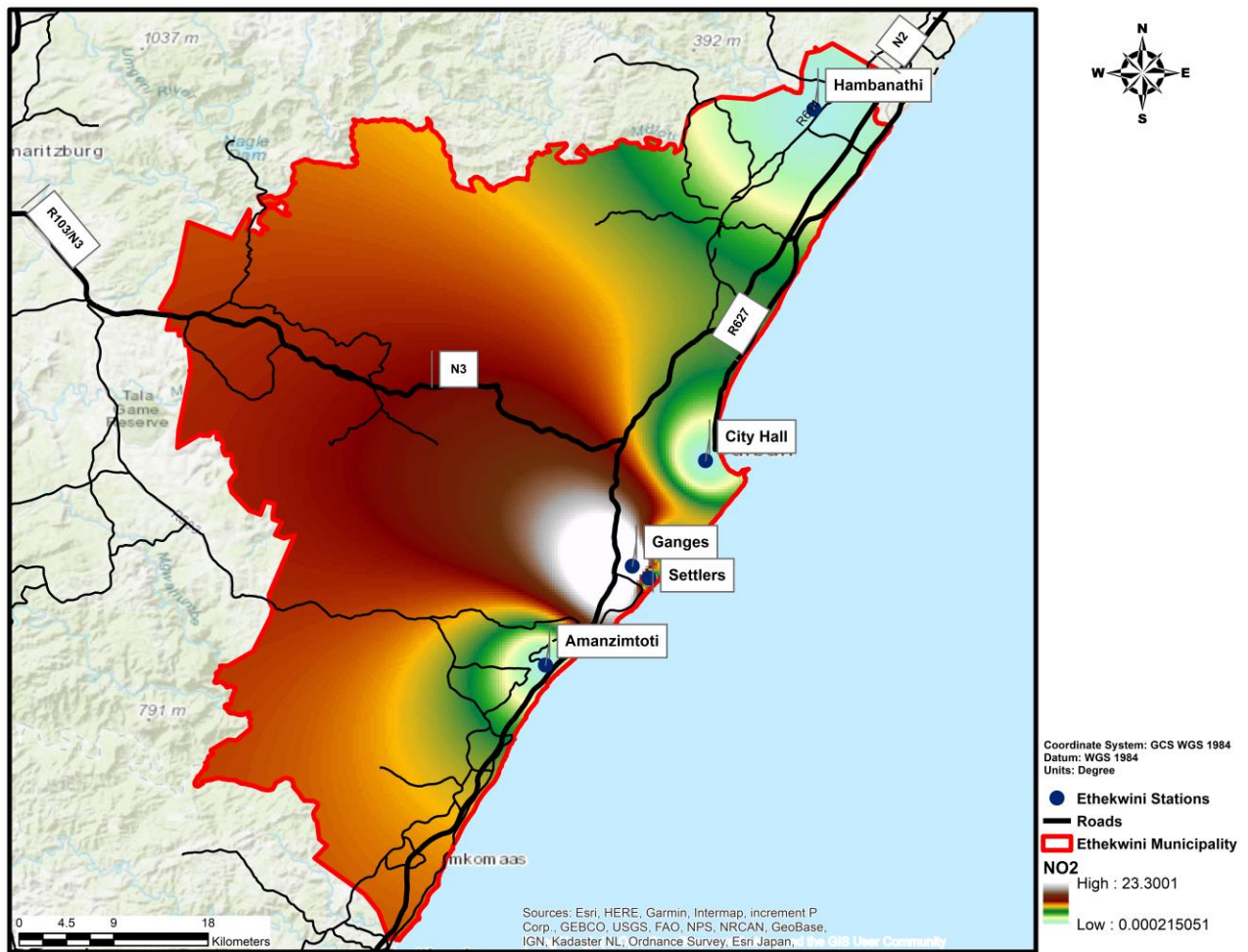


Figure 5.25 Spatial distribution of NO₂ at the eThekweni Municipality

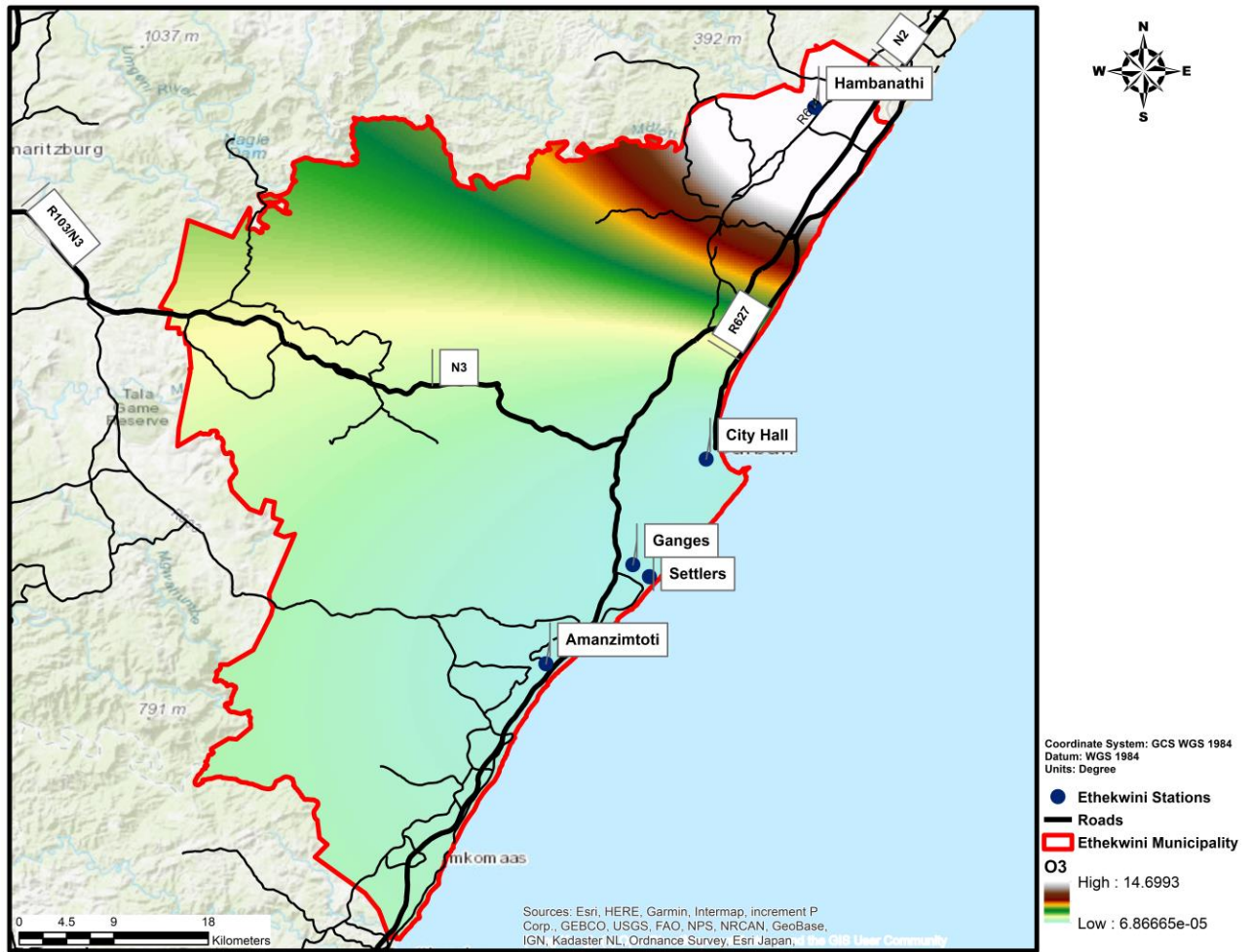


Figure 5.26 Spatial distribution of O₃ at the eThekweni Municipality

5.5.5.2 The Msunduzi Municipality

Figure 5.27 shows a spatial distribution of the annual average concentrations of PM_{2.5}, PM₁₀, SO₂, NO₂ and O₃ in Msunduzi Municipality. Figure 5.27 and Figure 5.28 demonstrate that concentrations of PM_{2.5} and PM₁₀ is high at the Pietermaritzburg Airport, it spreads to Edendale and its surroundings and decreases as the distance increases, which explains the low concentration observed in the Pietermaritzburg CBD. On the other hand, Figure 5.29 demonstrate that SO₂ concentration is high in Edendale, spreading to the surrounding areas, with the Pietermaritzburg CBD having a low concentration, and the SO₂ concentration decreases with the increasing distance. The NO₂ concentration was very high at the Pietermaritzburg Airport and a medium concentration was observed in the Pietermaritzburg CBD, with a gradual decrease in the concentration as the distance increases, refer to Figure 5.30. The O₃ concentration is very high at the Pietermaritzburg Airport and its concentration spreads to Edendale, although the concentration decreases as the distance increases, with the spread of the O₃ concentration to the Pietermaritzburg CBD being very low, refer to Figure 5.31.

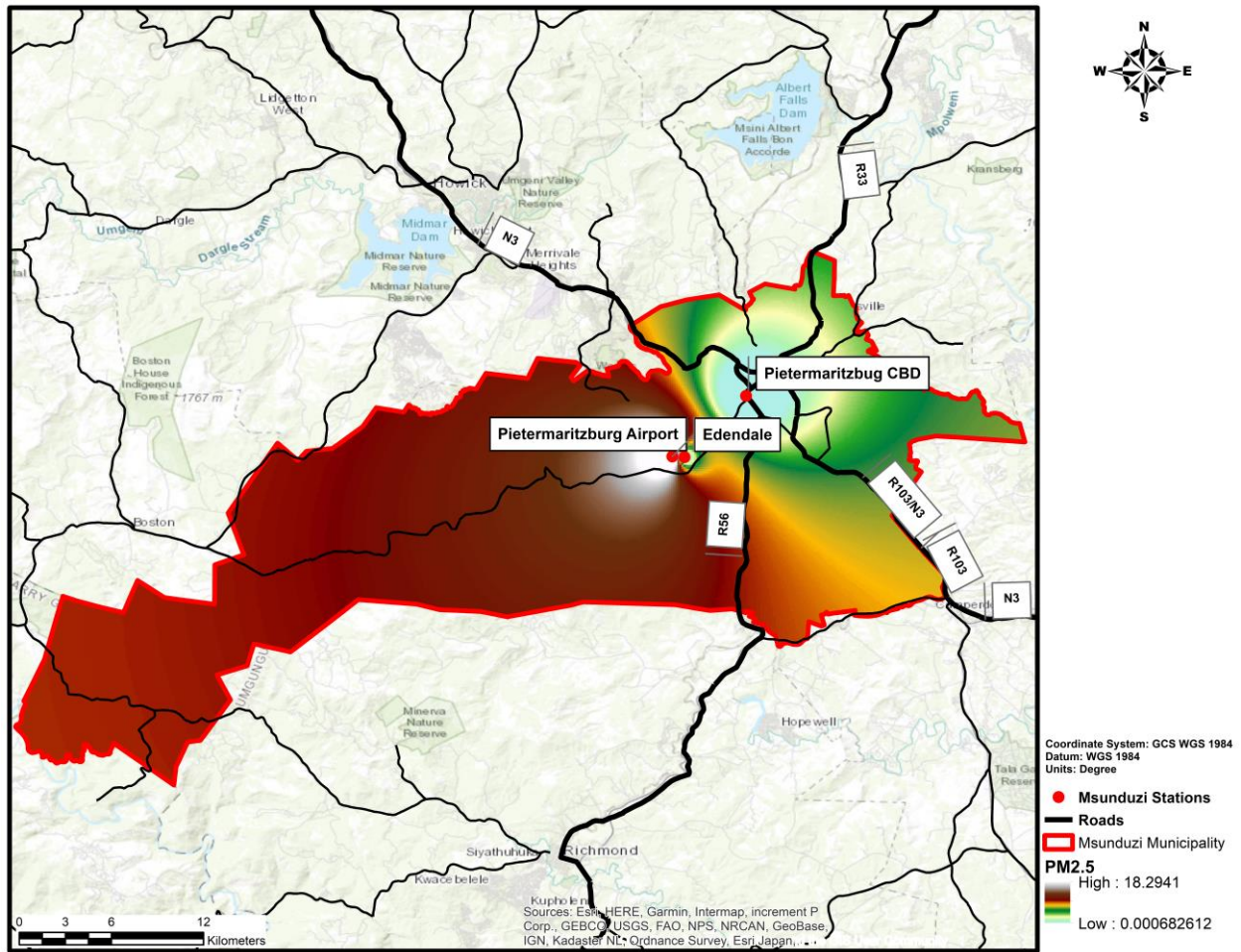


Figure 5.27 Spatial distribution of PM_{2.5} at the Msunduzi Municipality

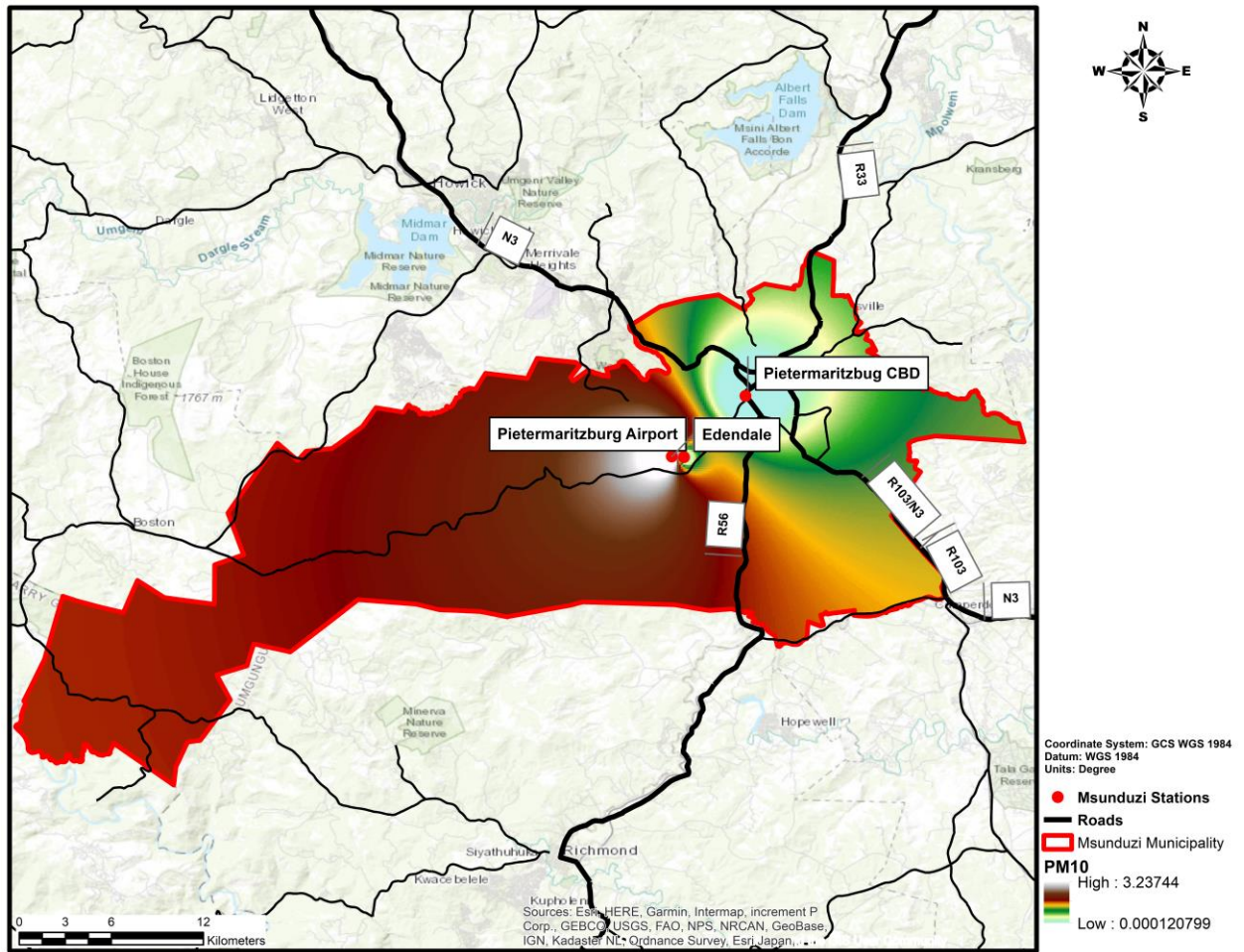


Figure 5.28 Spatial distribution of PM₁₀ at the Msunduzi Municipality

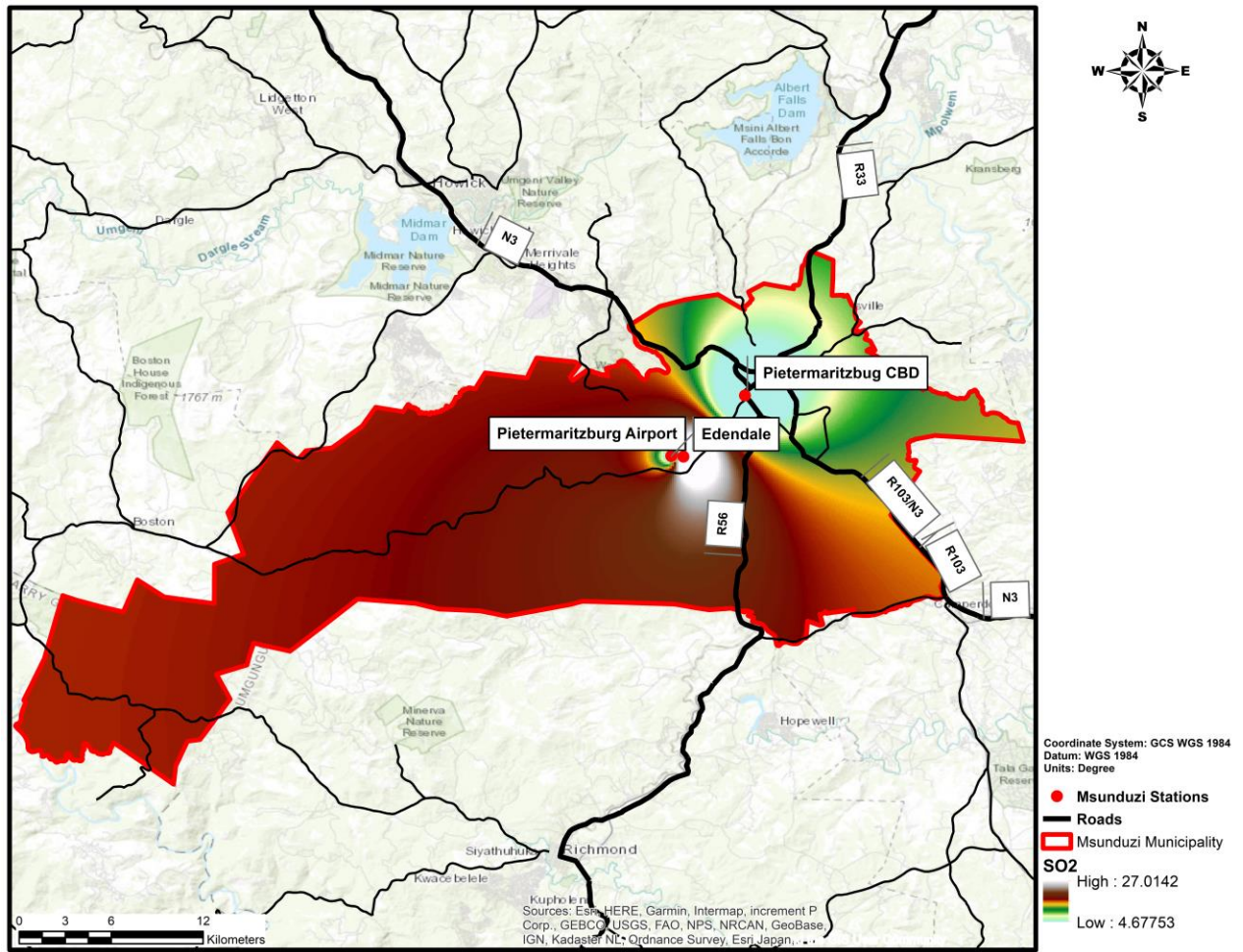


Figure 5.29 Spatial distribution of SO₂ at the Msunduzi Municipality

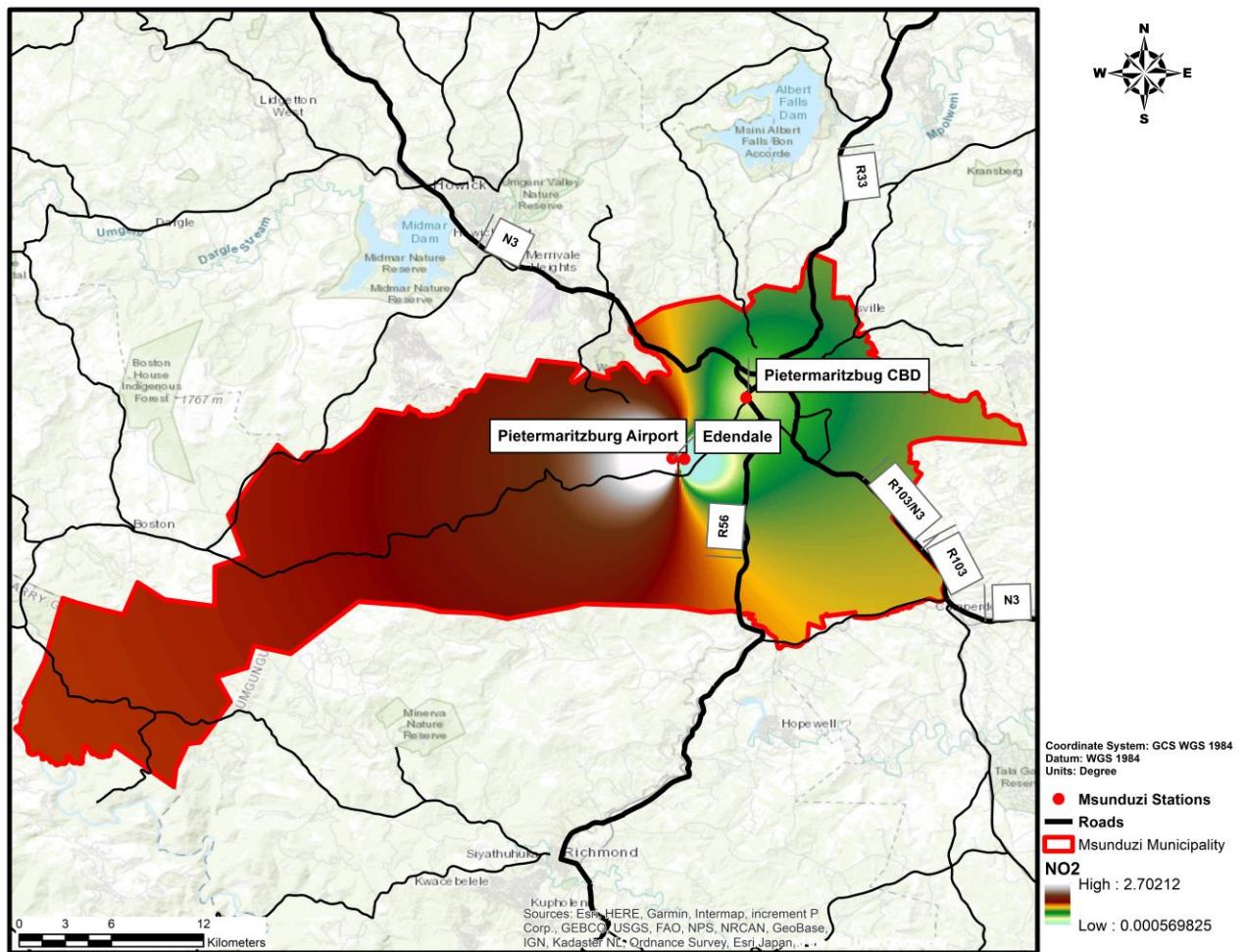


Figure 5.30 Spatial distribution of NO₂ at the Msunduzi Municipality

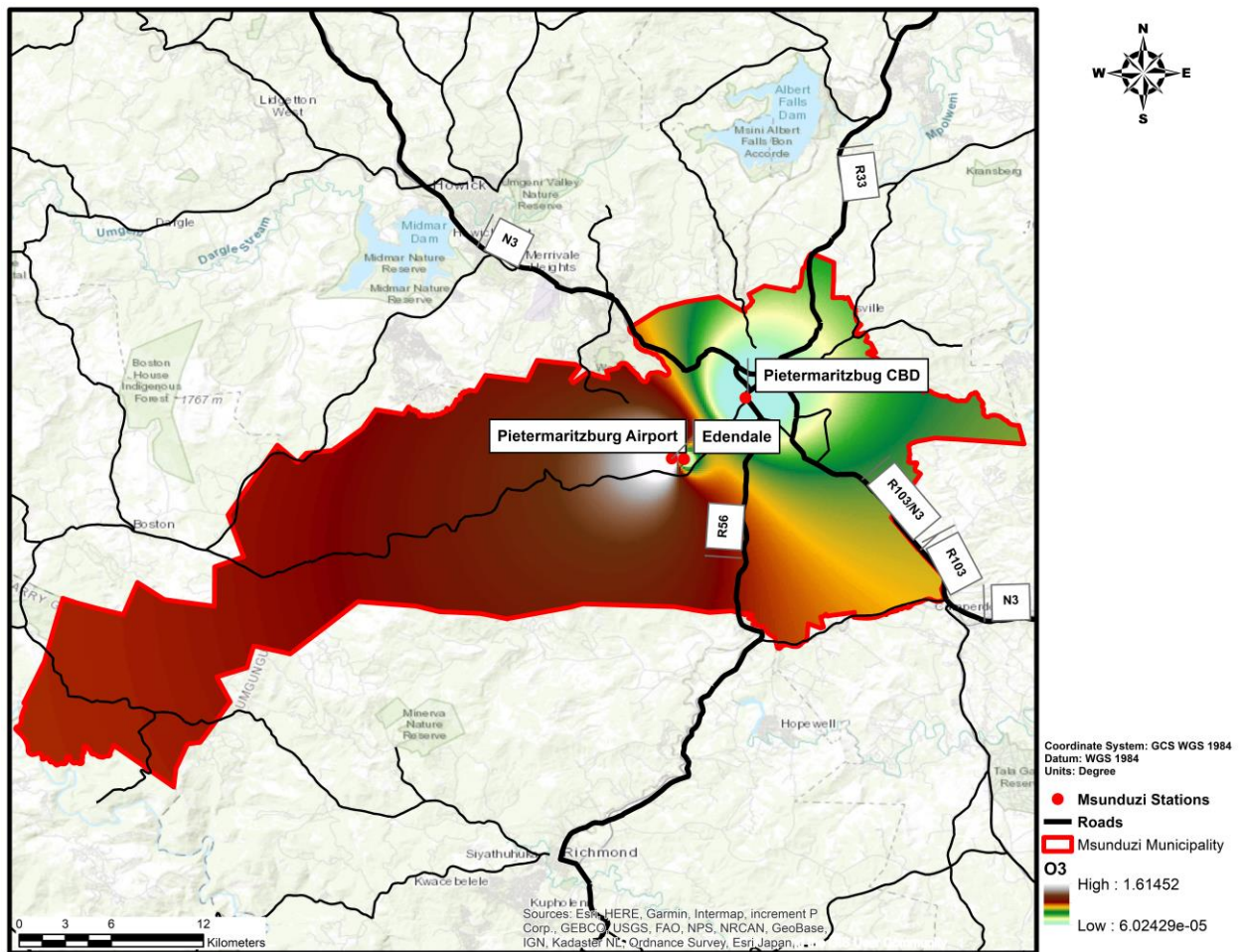


Figure 5.31 Spatial distribution of O₃ at the Msunduzi Municipality

5.3 Relationship between Air Pollutants and Meteorological Factors

Correlation of air pollutants and meteorological factors at Amanzimtoti

Table 5.2 shows the results of the linear relationship between SO₂ and the wind speed, wind direction, temperature and relative humidity in summer (DJF). The bivariate Pearson correlation with the wind speed was negative, weak and significant, ($r(1936) = -0.049$, $p < .05$). It was established that 0,2% of the variability in SO₂ concentration can be predicted by the variability of wind speed. The association between SO₂ and the wind direction was negative, weak and non-significant, ($r(1936) = -0.029$, $p > .05$), with only 0,1% of the variability being predicted by the wind direction. The association between SO₂ and the temperature was negative, weak and significant, ($r(1936) = -0.115$, $p < .05$), and only 1.3% of the variability of SO₂ can be predicted by the temperature. The

association between SO₂ and the relative humidity was positive, weak and significant, (r(1936)= .1800, p<.05), and 3.2% of the variability can be predicted.

In autumn (MAM) the bivariate Pearson correlation of the wind speed was positive, weak and significant, (r(2197)= .149, p<.05), with 2.2% of the variability being predicted by the wind speed. The association between SO₂ and the wind direction was negative, weak and significant, (r(2197)= -.265, p<.05), with 7% of the variability being predicted by the wind direction. The association between SO₂ and temperature was positive, weak and significant, (r(2197)= .124, p< .05), with 1.5% of variability being predicted by the temperature.

In winter (JJA), the bivariate Pearson correlation of SO₂ and wind speed was positive, relatively strong and significant, (r(1754)= .676, p<.05), with 45% of the variability being predicted by the wind speed. The relationship between the wind direction and SO₂ was negative, weak and significant, (r(2004)= -.452, p<.05), with 20% of the variability being predicted by the wind direction. The association between the temperature and SO₂ was positive, weak and non-significant, (r(1956)= .020, p>.05), with no variability. The relative humidity and SO₂ were negative, weak and significant, (r(570)= -.328, p<.05), with a 10% variability being predicted by the relative humidity.

In spring (SON) the bivariate Pearson correlation of SO₂ and wind speed was positive, weak and non-significant, (r(735)= .040, p>.05), with a 0.2% variability being predicted by the wind speed. The association between the wind direction and SO₂ was negative, weak and significant, (r(946)= -.221, p<.05), with a 4.9% variability being predicted by the wind direction. The SO₂ and temperature was negative, weak and significant, (r(945)= -.138, p<.05), with 1.9% of the variability being predicted by the temperature. The association with relative humidity was negative, weak and significant, (r(946)= -.225, p<.05), with a 5.1% variability being predicted by the relative humidity.

Table 5.2 Seasonal correlation between air pollutant concentration and meteorological factors in Amanzimtoti

SO ₂		WS	WD	Temp	RelHum%
Season	Pearson Correlation	-.049*	-.029	-.115**	.1800**

	Sig. (2-tailed)	.031	.210	.000	.000
	N	1936	1936	1936	740
	R ²	.002	.001	.013	.032
Autumn	Pearson Correlation	.149**	-.265**	.124**	.
	Sig. (2-tailed)	.000	.000	.000	.
	N	2197	2197	2197	.
	R ²	.022	.070	.015	.
Winter	Pearson Correlation	.676**	-.452**	.020	-.328**
	Sig. (2-tailed)	.000	.000	.377	.000
	N	1754	2004	1956	570
	R ²	.456	.204	.000	.108
Spring	Pearson Correlation	.040	-.221**	-.138**	-.225**
	Sig. (2-tailed)	.279	.000	.000	.000
	N	735	946	945	946
	R ²	.002	.049	.019	.051
*. Correlation is significant at the 0.05 level (2-tailed).					
**. Correlation is significant at the 0.01 level (2-tailed).					
a. Predictors: (Constant)					
b. Cannot be computed because at least one of the variables is constant.					

Figure 5.32 indicates that the highest wind speed during the summer (DJF) months ranged from 6-20.2 m/s¹, with south-westerly winds prevailing 25% of the time during the sampling period, the direction of the least frequency was east and south-east 7% of the time, and the highest calmness of the wind during this period was at 2%. During autumn (MAM), the highest wind speed ranged from 6-20.2 m/s¹, with wind blowing in a south-westerly direction 23% of the time, the direction of the least frequency was blowing from south-east 9% of the time, and the average calmness of the wind was 0.2%. During the winter months, the highest wind speed ranged from 6-20.2 m/s¹, with a south-westerly wind prevailing an average of 26% of the time, the direction of the least frequency was blowing from north-east 8% of the time, ranging from 4-6 m/s¹, and the average calmness of the wind was 0.2%. Lastly, in spring (SON) the highest wind speed ranged from 6-20.2 m/s¹, with south-westerly wind prevailing for an average of 22% of the time, the direction of

the least frequency was blowing from the north-east for 8% of the time, ranging from 6-20.2 m/s¹, and the average calmness of the wind was 0.1%.

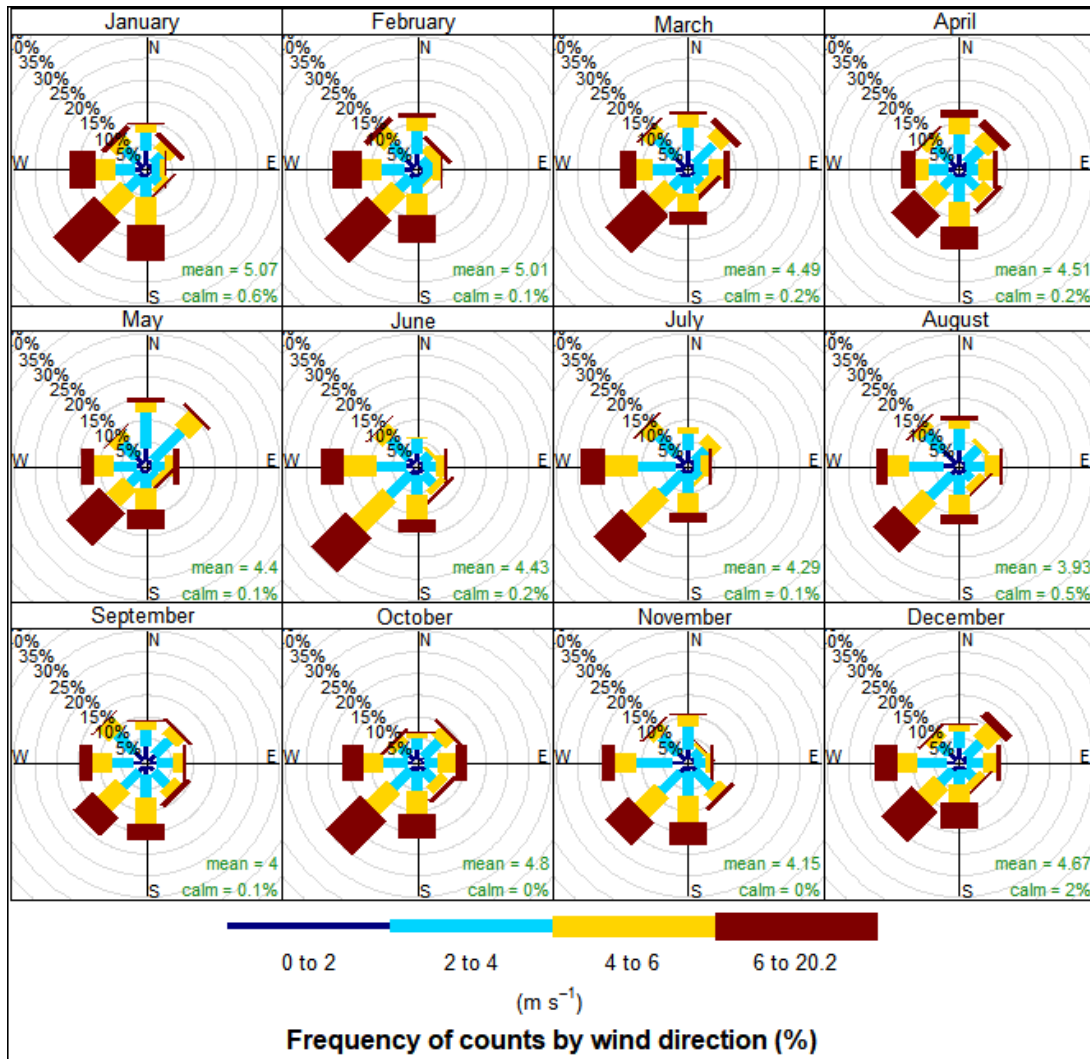


Figure 5.32 Wind roses for Amanzimtoti

Correlation of air pollutants and meteorological factors at Hambanathi

Table 5.3 shows the linear relationship between O₃ and the wind speed, wind direction, temperature, and relative humidity in summer (DJF). The bivariate Pearson correlation with the wind speed was positive, weak and significant, ($r(680) = .382, p < .05$). It was established that 14% of the variability in the O₃ concentration can be predicted by the wind speed variability. The association between O₃ and the wind direction was negative, weak and non-significant, ($r(1130) = -.219, p > .05$), with only 4.8% of the variability in the wind direction being predicted. The

association between O₃ and the relative humidity was negative, relatively strong and significant, (r(1131)= -.693, p<.05), with 48% of the variability being predicted by the relative humidity.

No data were available for autumn during the study period. In winter (JJA), the bivariate Pearson correlation was O₃ and the wind speed was negative, weak and non-significant, (r(41)= -.070, p>.05), with 0.5% of the variability being predicted by the wind speed. The relationship between the wind direction and O₃ was negative, weak and significant, (r(927)= -.296, p<.05), with 8% of the variability being predicted by the wind direction. The relative humidity and O₃ were positive, strong and significant, (r(927)= .770, p<.05), with 59% of the variability being predicted by the relative humidity.

In spring (SON), the bivariate Pearson correlation of O₃ and wind direction was negative, weak and significant, (r(1994)= -.101, p>.05), with 10% of the variability being predicted by the wind direction. The association between O₃ and the relative humidity was positive, weak and significant, (r(1994)= .499, p<.05), with 24% of the variability being predicted by the relative humidity.

Table 5.3 Seasonal correlation between air pollutant concentration and meteorological factors in Hambanathi

O ₃				
		WS	WD	RelHum
Summer	Pearson Correlation	.382**	-.219**	-.693**
	Sig. (2-tailed)	.000	.000	.000
	N	680	1130	1131
	R ²	.146	.048	.480
Winter	Pearson Correlation	-.070	-.296**	.770**
	Sig. (2-tailed)	.664	.000	.000
	N	41	927	927
	R ²	.005	.088	.593
Spring	Pearson Correlation	. ^b	-.101**	.499**
	Sig. (2-tailed)	.	.000	.000
	N	0	1994	1994
	R ²	.	.010	.249
* . Correlation is significant at the 0.05 level (2-tailed).				
** . Correlation is significant at the 0.01 level (2-tailed).				
a. Predictors: (Constant)				
b. Cannot be computed because at least one of the variables is constant.				

Figure 5.33 indicates that the highest wind speed during the summer (DJF) months ranged from 6-20.2 m/s¹, with north-easterly winds prevailing 26% of the time during the sampling period, and the direction of the least frequency was westerly for 2% of the time, with a wind speed ranging from 0-2 m/s¹. During this period, the highest calmness of the wind was at 2%. No data were available for the wind speed and wind direction during the other seasons.

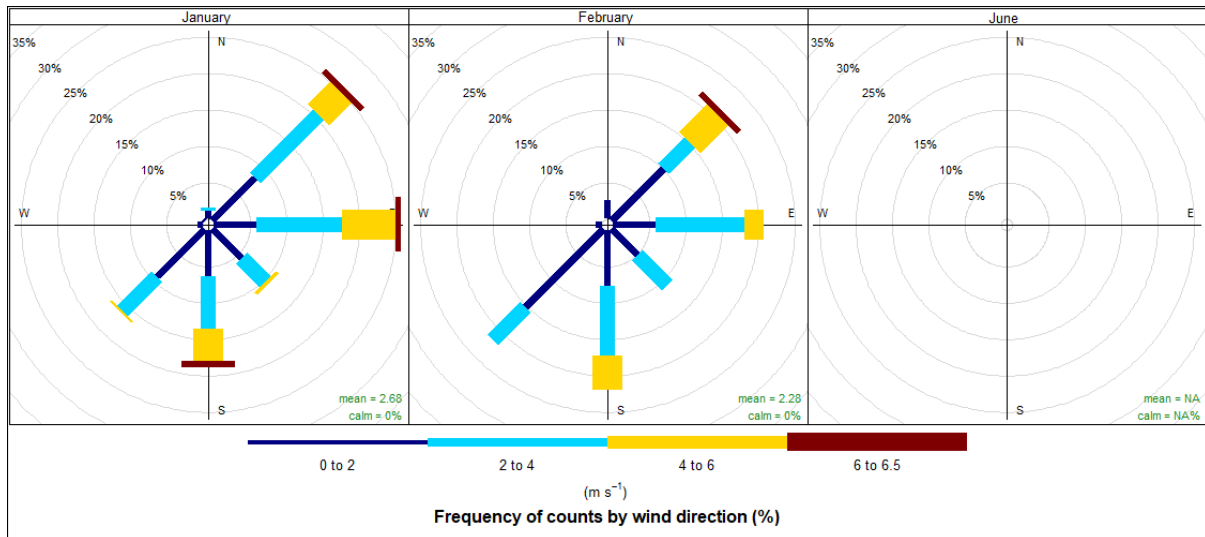


Figure 5.33 Wind roses for Hambanathi

Correlation of air pollutants and meteorological factors at Wentworth

Table 5.4 shows the linear relationship between SO_2 , $\text{PM}_{2.5}$ and PM_{10} and the wind speed, wind direction, temperature and relative humidity in summer (DJF). The bivariate Pearson correlation with the wind speed was positive, weak and significant, $r(1407) = .279$, $p < .05$ for SO_2 , and for both $\text{PM}_{2.5}$ and PM_{10} , the relationship with the wind was negative, weak and significant, $r(1411) = -.154$, $p < .05$ and $r(1411) = -.108$, $p < .05$, respectively. It was established that 7.8%, 2.8% and 1.2% of the variability in SO_2 , $\text{PM}_{2.5}$ and PM_{10} concentration, respectively, can be predicted by the wind speed. The association between the pollutants and wind direction was positive, weak and significant, $r(1407) = .167$, $p < .05$ for SO_2 , and negative, weak and significant, $r(1411) = -.047$, $p < .05$ and $r(1411) = -.191$, $p < .05$, for $\text{PM}_{2.5}$ and PM_{10} , respectively. The association between the pollutants and wind direction was 2.8%, 0.2% and 3.7% of the variability of the SO_2 , $\text{PM}_{2.5}$ and PM_{10} concentration, respectively, and it can be predicted by the wind direction. The association between the pollutants and temperature was negative, weak and non-significant, $r(1407) = -.020$ for SO_2 , $p > .05$. For $\text{PM}_{2.5}$ and PM_{10} , and the relationship was positive, weak and non-significant for $\text{PM}_{2.5}$ and significant for PM_{10} , $r(1411) = .043$, $p > .05$, $r(1411) = .055$, $p < .05$. The variability of the SO_2 , $\text{PM}_{2.5}$ and PM_{10} concentration that can be predicted by the temperature was 0.1%, 0.2% and 0.3%, respectively. The relationship between SO_2 , $\text{PM}_{2.5}$ and PM_{10} with relative humidity was negative, weak and non-significant, $r(1407) = -.027$, $p > .05$ for SO_2 , and for both $\text{PM}_{2.5}$ and PM_{10} , the relationship was positive, weak and significant, $r(1411) = .167$, $p < .05$ and $r(1411) = .077$, $p < .05$,

respectively. The variability of the SO₂, PM_{2.5} and PM₁₀ concentrations that can be predicted by the relative humidity was 0.1%, 2.8% and 0.6%, respectively.

In autumn (MAM), the bivariate Pearson correlation with the wind speed was positive, weak and significant, ($r(2199) = .233$, $p < .05$) for SO₂. For both PM_{2.5} and PM₁₀ the relationship with the wind was negative, weak and significant, ($r(2202) = -.349$, $p < .05$) and ($r(2202) = -.308$), $p < .05$), respectively. It was established that 5.4%, 12% and 9.5% of the variability in the SO₂, PM_{2.5} and PM₁₀ concentrations, respectively, can be predicted by the wind speed. The association of the pollutants and wind direction was positive, weak and significant for SO₂ and non-significant for PM_{2.5}, ($r(2199) = .104$, $p < .05$) and ($r(2202) = .014$, $p > .05$), and it was negative, weak and significant for PM₁₀, namely ($r(2202) = -.063$, $p < .05$). The association between the pollutants and wind direction was 1.1%, 0% and 0.4% of the variability of the SO₂, PM_{2.5} and PM₁₀ concentration, respectively, and can be predicted by wind direction. The association between the pollutants and temperature was positive, weak and non-significant for SO₂, ($r(2199) = .041$, $p > .05$), and for PM_{2.5} and PM₁₀ the relationship was negative, weak and significant, ($r(2202) = -.237$, $p < .05$), ($r(2202) = -.204$, $p < .05$). The variability of the SO₂, PM_{2.5} and PM₁₀ concentration that can be predicted by temperature was 0.2%, 5.6% and 4.2%, respectively. The association between SO₂, PM_{2.5} and PM₁₀ with the relative humidity was negative, weak and significant for SO₂, it was non-significant for PM₁₀, ($r(2199) = -.218$, and $p < .05$ and $r(2202) = -.034$, $p > .05$), respectively, and for PM_{2.5}, the relationship was positive, weak and significant, ($r(2202) = .046$, $p < .05$). The variability of the SO₂, PM_{2.5} and PM₁₀ concentration that can be predicted by the relative humidity was 4.7%, 0.2% and 0.1%, respectively.

In winter (JJA), the bivariate Pearson correlation with the wind speed was positive, weak and significant, ($r(1767) = .301$, $p < .05$) for SO₂, while for both PM_{2.5} and PM₁₀, the relationship with the wind speed was negative, weak and significant, ($r(1668) = -.425$, $p < .05$ and $r(1668) = -.411$, $p < .05$), respectively. It was established that 9.1%, 18% and 16% of the variability in the SO₂, PM_{2.5} and PM₁₀ concentration, respectively, can be predicted by the wind speed. The association of the pollutants and wind direction was positive, weak significant for SO₂ and non-significant for PM_{2.5}, ($r(1790) = .124$, $p < .05$ and $r(1690) = .008$, $p > .05$), respectively, and it was negative, weak and significant for PM₁₀, ($r(2202) = -.053$, $p < .05$). The association between the pollutants and the wind direction was 1.5%, 0% and 0.4% of the variability of the SO₂, PM_{2.5} and PM₁₀ concentration, respectively, and it can be predicted by the wind direction. The association between the pollutants

and the temperature was positive, weak and significant for SO₂, while for PM_{2.5} and PM₁₀ the relationship was negative, weak and significant, ($r(2043) = -.182, p < .05$ and $r(2043) = -.116, p < .05$), respectively. The variability of the SO₂, PM_{2.5} and PM₁₀ concentration that can be predicted by temperature was 2%, 3.3% and 1.4%, respectively. The association between SO₂, PM_{2.5} and PM₁₀ and the relative humidity was negative, weak and significant for SO₂ and non-significant for PM₁₀, ($r(2143) = -.144, p < .05$ and $r(2043) = -.026, p > .05$), respectively, and for PM_{2.5} the relationship was positive, weak and non-significant, ($r(2043) = .012, p > .05$). The variations in SO₂, PM_{2.5} and PM₁₀ concentrations predicted by relative humidity are 2.1%, 0%, and 0.1%, respectively.

In spring (SON), the bivariate Pearson correlation with the wind speed was positive, weak and significant for SO₂ and non-significant for PM_{2.5} and PM₁₀, ($r(372) = .479, p < .05$, $r(349) = .024, p > .05$ and $r(349) = .077, p > .05$), respectively. It was established that 22%, 0.1% and 0.6% of the variability in the SO₂, PM_{2.5} and PM₁₀ concentration, respectively, can be predicted by the wind speed. The association of the pollutants and wind direction was positive, weak and non-significant for SO₂ and significant for PM_{2.5} and PM₁₀, ($r(372) = .092, p > .05$, $r(349) = .273, p < .05$ and $r(349) = .264, p < .05$), respectively. The association between the pollutants and wind direction was 0.9%, 7.5% and 7% of the variability of the SO₂, PM_{2.5} and PM₁₀ concentration, respectively, and it can be predicted by the wind direction. The association between the pollutants and the temperature was positive, weak and non-significant for SO₂ and PM_{2.5}, significant for PM₁₀, ($r(373) = .049, p > .05$ for SO₂, $r(350) = .074, p > .05$ for PM_{2.5} and $r(350) = .151, p < .05$ for PM₁₀). The variability of the SO₂, PM_{2.5} and PM₁₀ concentration that can be predicted by the temperature were 0.2%, 0.6% and 2.3%, respectively. The association between SO₂, PM_{2.5} and PM₁₀ with the relative humidity was negative, weak and non-significant for SO₂ and PM_{2.5}, but significant for PM₁₀, ($r(373) = -.029, p > .05$, $r(350) = -.053, p > .05$ and $r(350) = -.142, p < .05$), respectively. Variability of the SO₂, PM_{2.5} and PM₁₀ concentration that can be predicted by relative humidity was 0.1%, 0.3% and 2%, respectively.

Table 5.4 Seasonal correlation between air pollutant concentration and meteorological factors in Wentworth

		SO ₂				PM _{2,5}				PM ₁₀			
		WS	WD	Temp	RelHum	WS	WD	Temp	RelHum	WS	WD	Temp	RelHum
Summer	Pearson Correlation	.279**	.167**	-.020	-.027	-	-.047	.043	.167**	-.108**	-	.055*	.077**
	Sig. (2-tailed)	.000	.000	.460	.303	.000	.080	.110	.000	.000	.000	.040	.004
	N	1407	1407	1407	1407	1411	1411	1411	1411	1411	1411	1411	1411
	R ²	.078	.028	.000	.001	.024	.002	.002	.028	.012	.037	.003	.006
Autumn	Pearson Correlation	.233**	.104**	.041	-.218**	-	.014	-	.046*	-.308**	-	-.204**	-.034
	Sig. (2-tailed)	.000	.000	.055	.000	.000	.518	.000	.030	.000	.003	.000	.110
	N	2199	2199	2199	2199	2202	2202	2202	2202	2202	2202	2202	2202
	R ²	.054	.011	.002	.047	.122	.000	.056	.002	.095	.004	.042	.001
Winter	Pearson Correlation	.301**	.124**	.142**	-.144**	-	.008	-	.012	-.411**	-.053*	-.116**	-.026
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.739	.000	.582	.000	.030	.000	.233
	N	1767	1790	2143	2143	1668	1690	2043	2043	1668	1690	2043	2043

	R ²	.091	.015	.020	.021	.180	.000	.033	.000	.169	.003	.014	.001
	Adj R ²	.090	.015	.020	.020	.180	-.001	.033	.000	.168	.002	.013	.000
Spring	Pearson Correlation	.479**	.092	.049	-.029	.024	.273**	.074	-.053	.077	.264**	.151**	-.142**
	Sig. (2-tailed)	.000	.076	.345	.580	.656	.000	.165	.322	.151	.000	.005	.008
	N	372	372	373	373	349	349	350	350	349	349	350	350
	R ²	.229	.009	.002	.001	.001	.075	.006	.003	.006	.070	.023	.020

*. Correlation is significant at the 0.05 level (2-tailed).

** . Correlation is significant at the 0.01 level (2-tailed).

b. Cannot be computed because at least one of the variables is constant.

Figure 5.34 indicates that the highest wind speed during the summer (DJF) months ranged from 6-13.4 m/s¹, with north-easterly winds prevailing 38% of the time during the sampling period, and direction of the least frequency was east and north-east 5% of the time, with a calmness of 0%. During autumn (MAM), the highest wind speed ranged from 6-20.2, with the wind blowing in a north-easterly direction 48% of the time, the direction of the least frequency was blowing from the north-west 3% of the time and the average calmness of the wind was 0%. During the winter months, the highest wind speed ranged from 6-13.42 m/s¹, with north-easterly winds prevailing for an average of 38% of the time, the direction of the least frequency was blowing from the north-west 10% of the time, ranging from 2-4 m/s¹, and the average calmness of the wind was 0%. Lastly, during spring (SON), the highest wind speed ranged from 2-4 m/s¹ with a southerly wind prevailing average 60% of the time, the direction of the least frequency was blowing from the north-west 3% of the time, ranging from 0-2 m/s¹, and the average calmness of the wind was 4.9%.

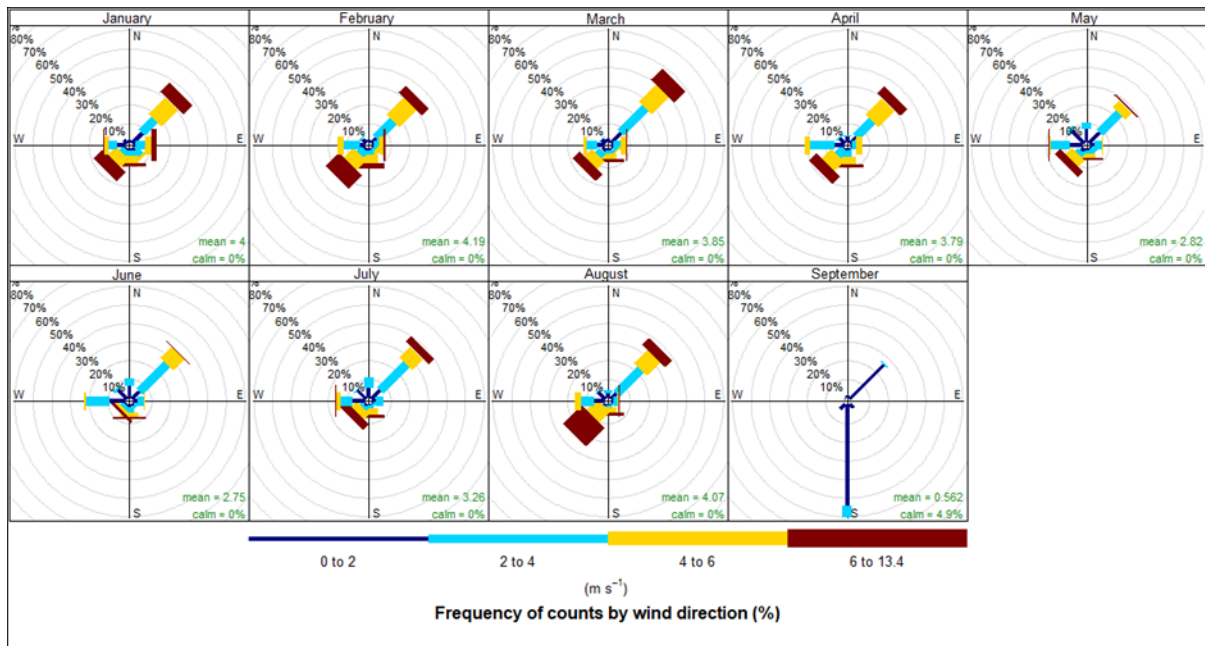


Figure 5.34 Wind roses for Wentworth

Correlation of air pollutants and meteorological factors at Edendale

Table 5.5 shows the linear relationship between SO₂ and the wind speed, wind direction, temperature and relative humidity. In summer (DJF), bivariate Pearson correlation with the wind speed was negative, weak and significant, $r(1554) = -0.178$, $p < 0.05$. It was established that 3.2% of the variability in SO₂ concentration can be predicted by the variability of the wind speed. The association between SO₂ and the wind direction was positive, weak and non-significant, $r(1554) = 0.010$, $p > 0.05$, with no variability to predict SO₂. The association between SO₂ and the temperature was negative, weak and significant, $r(1554) = -0.250$, $p < 0.05$, and 6.3% of the variability of SO₂ can be predicted by the temperature. The association between SO₂ and the relative humidity was positive, weak and non-significant, $r(1554) = 0.020$, $p > 0.05$, with no variability to predict SO₂.

In autumn (MAM), the bivariate Pearson correlation of wind speed was negative, weak and significant, $r(1710) = -0.581$, $p < 0.05$, with 33.8% of the variability being predicted by the wind speed. The association between SO₂ and the wind direction was positive, weak and significant, $r(1710) = -0.273$, $p < 0.05$, with 7.4% of the variability being predicted by the wind direction. The association between SO₂ and the temperature was negative, weak and significant, $r(1710) = -0.237$, $p < 0.05$, with 5.6% of the variability being predicted by the temperature. The association between SO₂ and the relative humidity was positive, weak and significant, $r(1710) = -0.182$, $p < 0.05$, with 3.3% of the variability being predicted by the relative humidity.

In winter (JJA) the bivariate Pearson correlation of SO₂ and the wind speed was negative, weak and significant, $r(1411) = -0.568$, $p < 0.05$, with 32% of the variability being predicted by the wind speed. The relationship of the wind direction and SO₂ was positive, weak and significant, $r(1411) = 0.175$, $p < 0.05$, with 3.1% of the variability being predicted by the wind direction. The association between the temperature and SO₂ was negative, weak and significant, $r(1411) = -0.211$, $p > 0.05$, with 4.5% of the variability being predicted by the temperature. The association between the relative humidity and SO₂ was positive, weak and significant, $r(1411) = 0.098$, $p < 0.05$, with a 1% variability being predicted by the relative humidity.

In spring (SON), the bivariate Pearson correlation of SO₂ and wind speed was negative, weak and significant, $r(2022) = -0.619$, $p < 0.05$, with a 38% variability being predicted by the wind speed. The association between the wind direction and SO₂ was positive, weak and significant, $r(2022) = 0.169$, $p < 0.05$, with a 2.9% variability being predicted by the wind direction. The SO₂ and temperature

were negative, weak and significant, $r(2022) = -0.440$, $p < 0.05$, with 19.4% of the variability being predicted by the temperature. The association with the relative humidity was positive, weak and significant, $r(2022) = 0.246$, $p < 0.05$, with a 6.1% variability being predicted by the relative humidity.

Table 5.5 Seasonal correlation between air pollutant concentration and meteorological factors in Edendale

SO ₂					
		WS	WD	Temp	RelHum
Summer	Pearson Correlation	-.178**	.010	-.250**	.020
	Sig. (2-tailed)	.000	.691	.000	.442
	N	1554	1554	1554	1554
	R ²	.032	.000	.063	.000
Autumn	Pearson Correlation	-.581**	.273**	-.237**	.182**
	Sig. (2-tailed)	.000	.000	.000	.000
	N	1710	1710	1710	1710
	R ²	.338	.074	.056	.033
Winter	Pearson Correlation	-.568**	.175**	-.211**	.098**
	Sig. (2-tailed)	.000	.000	.000	.000
	N	1411	1411	1411	1411
	R ²	.323	.031	.045	.010
Spring	Pearson Correlation	-.619**	.169**	-.440**	.246**
	Sig. (2-tailed)	.000	.000	.000	.000
	N	2022	2022	2022	2022
	R ²	.383	.029	.194	.061
*. Correlation is significant at the 0.05 level (2-tailed).					
**. Correlation is significant at the 0.01 level (2-tailed).					
a. Predictors: (Constant)					
b. Cannot be computed because at least one of the variables is constant.					

Figure 5.35 indicates that the highest wind speed during the summer (DJF) months ranged from 4-11.7 m/s¹, with easterly winds prevailing 30% of the time during the sampling period, and the

direction of the least frequency was westerly 3% of the time, ranging from 0.2 m/s¹. During this period, the calmness of the wind was at 0%. During autumn (MAM), the highest wind speed ranged from 4-6, with the wind blowing in an easterly direction 25% of the time, while the direction of the least frequency was blowing from the west 3% of the time, with a wind speed ranging from 0-2 m/s¹, and the average calmness of the wind was 0%. During the winter months, the highest wind speed ranged from 6-11.7 m/s¹, with south-westerly winds prevailing, on average, 26% of the time, the direction of the least frequency blowing from the north-west 3% of the time, with a wind speed ranging from 6-11.7 m/s¹, and the average calmness of the wind was 0%. Lastly, the highest wind speed in spring (SON) ranged from 4-6 m/s¹, with an easterly wind prevailing for an average of 30% of the time, the direction of the least frequency was blowing from the north-west 3% of the time, with wind speed ranging from 6-11.7 m/s¹, and the average calmness of the wind was 0%.

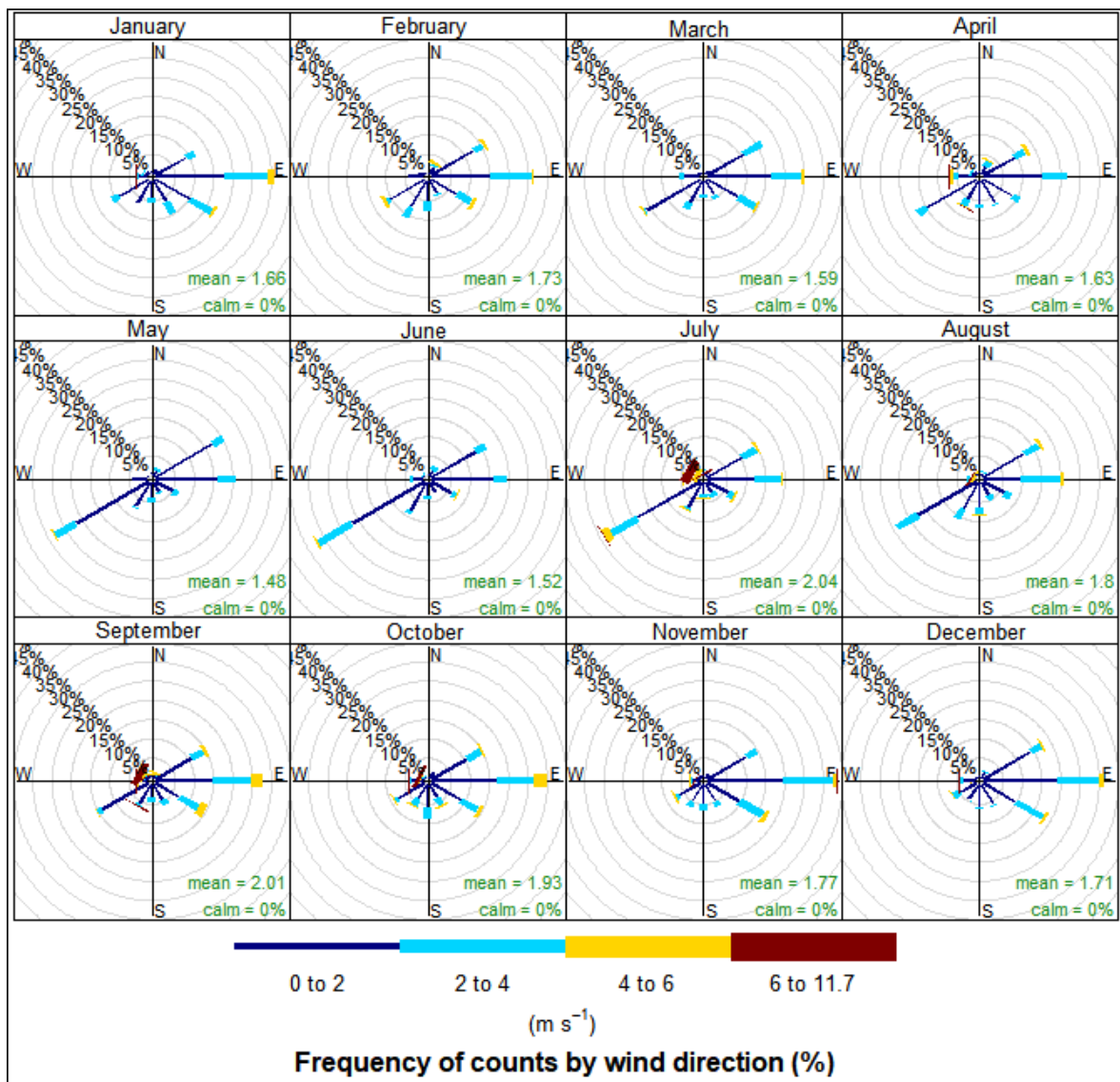


Figure 5.35 Wind roses for Edendale

Correlation of air pollutants and meteorological factors in the Pietermaritzburg CBD

Table 5.6 shows linear relationship between SO₂, NO₂ and the wind speed, wind direction, temperature and relative humidity. In summer (DJF), bivariate Pearson correlation with the wind speed was negative, weak and significant for SO₂ and non-significant for NO₂, $r(1973) = -0.149$, $p < 0.05$ and $r(1973) = -0.033$, $p > 0.05$, respectively. It was established that 2.2% and 0.1% of the variability in the SO₂ and NO₂ concentration, respectively, can be predicted by the variability of the wind speed. The association of SO₂ and NO₂ with the wind direction was negative, weak and significant for SO₂ and non-significant for NO₂, $r(1973) = -0.159$, $p < 0.05$ and $r(1973) = -0.036$, $p < 0.05$, respectively. A variability of 2.5% and 0.1% for SO₂ and NO₂, respectively, can be predicted by

the variability of the wind direction. The association between SO₂, NO₂ and the temperature was positive, weak and non-significant, $r(1973) = .042$, $p > .05$ and $r(1973) = -.031$, $p > .05$, respectively. A variability of 0.2% and 0.1% for SO₂ and NO₂, respectively, can be predicted by the temperature. The association between SO₂, NO₂ and the relative humidity was negative, weak and significant for SO₂, $r(1973) = -.046$, $p < .05$, and positive, weak and non-significant for NO₂, $r(1973) = .035$, $p > .05$, with no variability for predicting the relative humidity from SO₂ and 0.1% of NO₂ to predict relative humidity.

In autumn (MAM), the bivariate Pearson correlation of SO₂ with the wind speed was negative, weak and significant, $r(1610) = -.214$, $p < .05$, with 4.6% of the variability being predicted by the wind speed. The association between SO₂ and the wind direction was negative, weak and significant, $r(1710) = -.232$, $p < .05$, with 5.4% of the variability being predicted by the wind direction. The association between SO₂ and the temperature was negative, weak and non-significant, $r(1610) = -.016$, $p > .05$, with no variability being predicted by the temperature. The association between SO₂ and the relative humidity was negative, weak and significant, $r(1610) = -.226$, $p < .05$, with 5.1% of the variability being predicted by the relative humidity.

In winter (JJA), the bivariate Pearson correlation of SO₂ with the wind speed and wind direction was negative, weak and significant, $r(1827) = -.088$, $p < .05$, with 0.8% of the variability being predicted by the wind speed and wind direction. Association between temperature and SO₂ was positive, weak and significant, $r(1827) = .166$, $p < .05$, with 2.8% of the variability being predicted by the temperature. The relative humidity and SO₂ were negative, weak and significant, $r(1827) = -.220$, $p < .05$, with 4.8% of the variability being predicted by the relative humidity.

In spring (SON), the bivariate Pearson correlation of SO₂ and NO₂ and the wind speed was positive, weak and non-significant, $r(2126) = .007$, $p > .05$ and $r(2126) = .002$, $p > .926$, respectively, with no variability in the SO₂ and NO₂ concentrations being predicted by the wind speed. The association between the wind direction and SO₂ was positive, weak and non-significant, $r(2126) = .006$, $p > .05$, and with NO₂ it was negative, weak and non-significant, with no variability in SO₂ and NO₂ being predicted by the wind direction. The relationship between SO₂ and NO₂ and the temperature was positive, weak and significant for SO₂ and non-significant for NO₂, $r(2126) = .309$, $p < .05$ and $r(2126) = .020$, $p > .05$, respectively. A variability of 9.5% of SO₂ can be predicted by temperature. The association between the pollutants and the relative humidity was negative, weak and significant for SO₂ and non-significant for NO₂, $r(2126) = -.342$, $p < .05$ for SO₂ and $r(2126) = -.025$,

p>.05 for NO₂, with 11% and 0.1%, respectively, of the variability being predicted by the relative humidity.

Table 5.6 Seasonal correlation between air pollutant concentration and meteorological factors in the Pietermaritzburg CBD

		SO ₂				NO ₂			
		WS	WD	Temp	RelHum	WS	WD	Temp	RelHum
Summer	Pearson Correlation	-.149**	-.159**	.042	-.046*	-.033	-.036	-.031	.035
	Sig. (2-tailed)	.000	.000	.059	.041	.143	.112	.168	.124
	N	1973	1973	1973	1973	1973	1973	1973	1973
	R ²	.022	.025	.002	.	.001	.001	.001	.001
Autumn	Pearson Correlation	-.214**	-.232**	-.016	-.226**	. ^a	. ^a	. ^a	. ^a
	Sig. (2-tailed)	.000	.000	.531	.000	.	.	.	.
	N	1610	1610	1610	1610	1610	1610	1610	1610
	R ²	.046	.054	.000	.051	.	.	.	.
Winter	Pearson Correlation	-.088**	-.088**	.166**	-.220**	. ^a	. ^a	. ^a	. ^a
	Sig. (2-tailed)	.000	.000	.000	.000	.	.	.	.
	N	1827	1827	1827	1827	1827	1827	1827	1827
	R ²	.008	.008	.028	.048	.	.	.	.
Spring	Pearson Correlation	.007	.006	.309**	-.342**	.002	-.003	.020	-.025
	Sig. (2-tailed)	.742	.776	.000	.000	.926	.872	.367	.247
	N	2126	2126	2126	2126	2126	2126	2126	2126
	R ²	.000	.000	.095	.117	.000	.000	.000	.001

*. Correlation is significant at the 0.05 level (2-tailed).

** . Correlation is significant at the 0.01 level (2-tailed).

a. Predictors: (Constant)

b. Cannot be computed because at least one of the variables is constant.

Figure 5.36 indicates that the highest wind speed during the summer (DJF), autumn (MAM), winter (JJA) and spring (SON) months ranged from 0-2 m/s¹, and that it blew in a northerly direction 100% of the time over these months. The calmness of the wind was 0% throughout the seasons.

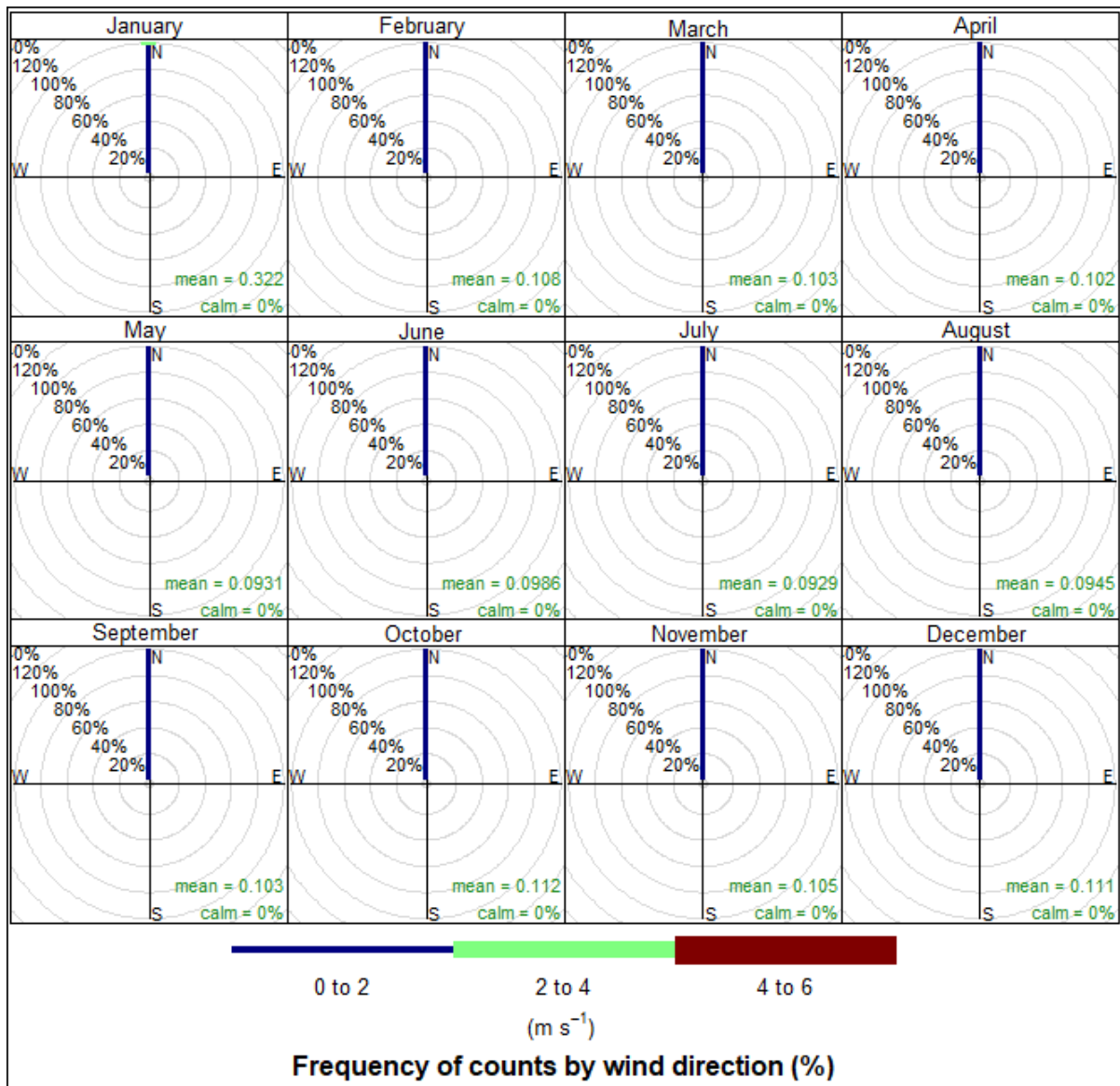


Figure 5.36 Wind roses for the Pietermaritzburg CBD

Correlation of air pollutants and meteorological factors at the Pietermaritzburg Airport

Table 5.7 shows the linear relationship between SO₂, NO₂, O₃, PM_{2.5} and PM₁₀ with the wind speed, wind direction, temperature and relative humidity during summer (DJF). The bivariate Pearson correlation with wind speed was positive, weak and significant, $r(1988) = .103$, $p < .05$ for SO₂, and $r(1988) = .164$, $p < .05$ for NO₂. A negative, weak and significant relationship was observed for O₃, PM_{2.5} and PM₁₀, $r(1988) = -.379$, $p < .05$, $r(1988) = -.014$, $p < .05$ and $r(1988) = -.190$, $p < .05$, respectively. It was established that 1.1%, 2.7%, 14.4%, 0% and 3.6% of the variability in SO₂, NO₂, O₃, PM_{2.5} and PM₁₀ concentrations, respectively, can be predicted by the wind speed. The association of the pollutants and wind direction was positive, weak and significant, $r(1988) = .140$, $p < .05$ for SO₂, and $r(1988) = .174$, $p < .05$ for NO₂, and for O₃, PM_{2.5}, PM₁₀, the relationship with the wind direction was negative, weak and significant, $r(1988) = -.474$, $p < .05$, $r(1988) = -.052$, $p < .05$ and $r(1988) = -.190$, $p < .05$, respectively. The association between the pollutants and wind direction was 2%, 3%, 22.5%, 1% and 3.6% of the variability of SO₂, NO₂, O₃, PM_{2.5} and PM₁₀ concentration, respectively, and they can be predicted by the wind direction. The association between the pollutants and temperature was negative, weak and non-significant for NO₂, $r(1988) = -.092$, $p > .05$, and the relationship with SO₂, O₃, PM_{2.5} and PM₁₀ was positive and weak for SO₂, PM_{2.5}, PM₁₀, strong for O₃, and significant, $r(1988) = .015$, $p < .05$ for SO₂, $r(1988) = .736$, $p < .05$ for O₃, $r(1988) = .057$, $p < .05$ for PM_{2.5} and $r(1988) = .194$, $p < .05$ for PM₁₀. The variability of the SO₂, NO₂, O₃, PM_{2.5} and PM₁₀ concentration that can be predicted by the temperature was 0%, 0.9%, 54%, 0.3% and 3.8%, respectively. The relationship between SO₂, NO₂, O₃, PM_{2.5} and PM₁₀ with the relative humidity was positive, weak and significant, $r(1988) = .089$, $p < .05$ for SO₂ and $r(1988) = .164$, $p < .05$ for NO₂, and the relationship was negative and strong for O₃ and weak for PM_{2.5} and PM₁₀. While it was significant for O₃, $r(1988) = -.736$, $p < .05$ for O₃, $r(1988) = -.016$, $p > .05$ for PM_{2.5} and PM₁₀, and non-significant for PM_{2.5} and $r(1988) = -.062$, $p < .05$ for PM₁₀. The variability of the SO₂, NO₂, O₃, PM_{2.5} and PM₁₀ concentrations that can be predicted by the relative humidity was 0.8%, 2.7%, 29.4%, 0% and 0.4%, respectively.

In autumn (MAM), the bivariate Pearson correlation with the wind speed was negative, weak and significant, $r(1700) = -.184$, $p < .05$ for SO₂, $r(1700) = -.291$, $p < .05$ for O₃ and $r(1700) = -.333$, $p < .05$ for PM₁₀, while a positive, weak and a significant relationship was observed for PM_{2.5}, $r(1700) = .075$, $p < .05$. It was established that 3.4%, 8.4%, 0.6%, and 11.1% of the variability in SO₂, O₃, PM_{2.5} and PM₁₀ concentration, respectively, can be predicted by the wind speed. The association

of the pollutants and wind direction was negative, weak and significant, $r(1700) = -0.111$, $p < 0.05$ for SO_2 , $r(1700) = -0.266$, $p < 0.05$ for O_3 and $r(1700) = -0.239$, $p < 0.05$ for PM_{10} , and for $\text{PM}_{2.5}$, the relationship with wind direction was positive, weak and non-significant, $r(1700) = 0.10$, $p > 0.05$. The association between the pollutants and wind direction was 0%, 7.1%, 0%, and 5.7% of the variability of SO_2 , O_3 , $\text{PM}_{2.5}$ and PM_{10} concentration, respectively, can be predicted by the wind direction. The association between the pollutants and temperature was negative, weak and non-significant for SO_2 , $r(1700) = -0.039$, $p > 0.05$, it was negative, weak and significant for PM_{10} , $r(1700) = -0.268$, $p < 0.05$, it was positive and weak for $\text{PM}_{2.5}$, and strong for O_3 , $r(1700) = 0.655$, $p < 0.05$, and significant for $\text{PM}_{2.5}$, $r(1700) = 0.263$, $p < 0.05$. The variability of the SO_2 , O_3 , $\text{PM}_{2.5}$ and PM_{10} concentration that can be predicted by the temperature was 0.2%, 42.9%, 6.9% and 6.9%, respectively. The relationship between SO_2 , O_3 , $\text{PM}_{2.5}$ and PM_{10} with the relative humidity was positive, weak and significant for $\text{PM}_{2.5}$, $r(1700) = 0.076$, $p < 0.05$, the relationship was negative and relatively strong for O_3 , $r(1700) = -0.670$, $p < 0.05$, and weak for SO_2 and PM_{10} , $r(1988) = -0.185$, $p < 0.05$ for SO_2 , and $r(1700) = -0.268$, $p < 0.05$ for PM_{10} . The variability of the SO_2 , O_3 , $\text{PM}_{2.5}$ and PM_{10} concentration that can be predicted by the relative humidity was 3.4%, 44.9%, 0.6% and 7.2%, respectively.

In winter (JJA), the bivariate Pearson correlation of air pollutants with the wind speed was negative, weak and significant, $r(2079) = -0.100$, $p < 0.05$ for SO_2 , $r(2079) = -0.122$, $p < 0.05$ for NO_2 , $r(2079) = -0.522$, $p < 0.05$ for O_3 and $r(2079) = -0.179$, $p < 0.05$ for PM_{10} . It was established that 1%, 1.5%, 27.2% and 5.9% of the variability in the SO_2 , NO_2 , O_3 and PM_{10} concentration, respectively, can be predicted by the wind speed. The association of the pollutants and wind direction was negative, weak and significant, $r(2079) = -0.114$, $p < 0.05$ for SO_2 , $r(2079) = -0.075$, $p < 0.05$ for NO_2 , $r(2079) = -0.534$, $p < 0.05$ for O_3 , and $r(2079) = -0.190$, $p < 0.05$ for PM_{10} . The association between the pollutants and wind direction was 1.3%, 0.6%, 28.5% and 3.6% of the variability of SO_2 , NO_2 , O_3 and PM_{10} concentration, respectively, and it can be predicted by the wind direction. The association between the pollutants and temperature was positive and weak for SO_2 and PM_{10} , and strong for O_3 and significant, $r(2079) = 0.144$, $p < 0.05$ for SO_2 , $r(2079) = 0.764$, $p < 0.05$ for O_3 , and $r(2079) = 0.058$, $p < 0.05$ for PM_{10} , and the relationship was negative, weak and significant for NO_2 , namely $r(2079) = -0.041$, $p < 0.05$. The variability of the SO_2 , NO_2 , O_3 , and PM_{10} concentration that can be predicted by the temperature was 2.1%, 0.2%, 58.3% and 0.3%, respectively. The association between SO_2 , NO_2 , O_3 , and PM_{10} and the relative humidity was negative and weak for SO_2 and PM_{10} , relatively strong for O_3 and significant, $r(2079) = -0.185$, $p < 0.05$ for SO_2 , $r(2079) = -0.688$, $p < 0.05$ for O_3 and $r(2079) = -$

.179, $p < .05$ for PM_{10} , and the relationship was positive, weak and significant for NO_2 , $r(2079) = .109$, $p < .05$. The variability of SO_2 , NO_2 , O_3 and PM_{10} concentration that can be predicted by the relative humidity was 3.4%, 1.2%, 47.4% and 3.2%, respectively.

In spring (SON), the bivariate Pearson correlation with the wind speed was negative, weak and significant for SO_2 and O_3 , $r(1794) = -.081$, $p < .05$ and $r(1794) = -.362$, $p < .05$, respectively, and relationship between NO_2 and the wind speed was positive, weak and significant, $r(1794) = .198$. It was established that 0.7%, 3.9% and 13.1% of the variability in SO_2 , NO_2 and O_3 concentration, respectively, can be predicted by the wind speed. The association of the pollutants and wind direction was negative, weak and significant for SO_2 and O_3 , $r(1794) = -.086$, $p < .05$ and $r(1794) = -.366$, $p < .05$, respectively, and relationship between NO_2 and the wind direction was positive, weak and significant, $r(1794) = .190$. The association between the pollutants and the wind direction was 0.7%, 3.6% and 13.4% of the variability of the SO_2 , NO_2 and O_3 concentration, respectively, and it can be predicted by the wind direction. The association between the pollutants and the temperature was positive, weak for SO_2 and NO_2 , but strong with O_3 and significant, $r(1794) = .138$, $p > .05$ for SO_2 , $r(1794) = .098$, $p > .05$ for NO_2 and $r(1794) = .711$, $p < .05$ for O_3 . The variability of the SO_2 , NO_2 and O_3 concentration that can be predicted by the temperature was 1.9%, 1% and 50.6%, respectively. The association between SO_2 , NO_2 and O_3 with the relative humidity was negative, weak for SO_2 and strong for O_3 and significant, $r(1794) = -.142$, $p < .05$ for SO_2 and $r(1794) = -.752$, $p < .05$ for O_3 , and the relationship was positive, weak and significant for NO_2 , $r(1794) = .137$, $p < .05$. The variability of the SO_2 , NO_2 , O_3 concentrations that can be predicted by the relative humidity were 2%, 1.9%, and 56.5%, respectively.

Table 5.7 Seasonal correlation between air pollutant concentration and meteorological factors at the Pietermaritzburg Airport

		SO ₂				NO ₂				O ₃				PM _{2,5}				PM ₁₀			
		W S	W D	Tem p	Rel Hum	WS	WD	Tem p	Rel Hum	W S	W D	Tem p	Rel Hum	W S	WD	Tem p	Rel Hum	WS	W D	Tem p	RelH um
Summer	Pears on Correl ation	.10 3**	.14 0**	.015	.089 **	.164 **	.174 **	- .092 **	.164 **	- .37 9**	- .47 4**	.736 **	- .771 **	- .01 4	- .052 *	.057 *	- .016	- .189 **	- .19 0**	.194 **	- .062* *
	Sig. (2- tailed)	.00 0	.00 0	.510	.000	.000	.000	.000	.000	.00 0	.00 0	.000	.000	.53 3	.022	.011	.474	.000	.00 0	.000	.005
	N	19 88	19 88	1988	1988	1988	1988	1988	1988	19 88	198 8	198 8	1988	19 88	1988	1988	1988	1988	19 88	198 8	1988
	R ²	.01 1	.02 0	.000	.008	.027	.030	.009	.027	.14 4	.22 5	.541	.594	.00 0	.003	.003	.000	.036	.03 6	.038	.004
Autumn	Pears on Correl ation	- .18 4**	- .11 1**	- .039	- .185 **	. a	. a	. a	. a	- .29 1**	- .26 6**	.655 **	- .670 **	.07 5**	.010	.263 **	.076 **	- .333 **	- .23 9**	- .263 **	- .268* *
	Sig. (2- tailed)	.00 0	.00 0	.106	.000	.	.	.	.	.00 0	.00 0	.000	.000	.00 2	.674	.000	.002	.000	.00 0	.000	.000

		SO ₂				NO ₂				O ₃				PM _{2,5}				PM ₁₀			
		W S	W D	Tem p	Rel Hum	WS	WD	Tem p	Rel Hum	W S	W D	Tem p	Rel Hum	W S	WD	Tem p	Rel Hum	WS	W D	Tem p	RelH um
	N	17 00	17 00	1700	1700	1700	1700	1700	1700	17 00	170 0	170 0	1700	17 00	1700	1700	1700	1700	17 00	170 0	1700
	R ²	.03 4	.01 2	.002	.034	.	.	.	.	.08 5	.07 1	.429	.449	.00 6	.000	.069	.006	.111	.05 7	.069	.072
Winter	Pears on Correl ation	- .10 0**	- .11 4**	.144 **	- .185 **	- .122 **	- .075 **	- .041	.109 **	- .52 2**	- .53 4**	.764 **	- .688 **	. ^b	. ^b	. ^b	. ^b	- .243 **	- .19 0**	.058 **	- .179* *
	Sig. (2- tailed)	.00 0	.00 0	.000	.000	.000	.001	.064	.000	.00 0	.00 0	.000	.000	.	.	.	.	.000	.00 0	.009	.000
	N	20 79	20 79	2079	2079	2079	2079	2079	2079	20 79	207 9	207 9	2079	20 79	2079	2079	2079	2079	20 79	207 9	2079
	R ²	.01 0	.01 3	.021	.034	.015	.006	.002	.012	.27 2	.28 5	.583	.474	.	.	.	.	.059	.03 6	.003	.032
Spring	Pears on Correl ation	- .08 1**	- .08 6**	.138 **	- .142 **	.198 **	.190 **	.098 **	.137 **	- .36 2**	- .36 6**	.711 **	- .752 **	. ^b	. ^b	. ^b	. ^b	. ^b	. ^b	. ^b	. ^b

		SO ₂				NO ₂				O ₃				PM _{2,5}				PM ₁₀			
		W S	W D	Tem p	Rel Hum	WS	WD	Tem p	Rel Hum	W S	W D	Tem p	Rel Hum	W S	WD	Tem p	Rel Hum	WS	W D	Tem p	RelH um
	Sig. (2- tailed)	.00 1	.00 0	.000	.000	.000	.000	.000	.000	.00 0	.00 0	.000	.000	.	.	.	.	.	.	.	.
	N	17 94	17 94	1794	1794	1794	1794	1794	1794	17 94	179 4	179 4	1794	17 94	1794	1794	1794	1794	17 94	179 4	1794
	R ²	.00 7	.00 7	.019	.020	.039	.036	.010	.019	.13 1	.13 4	.506	.565	.	.	.	.	.	.	.	.

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

a. Predictors: (Constant)

b. Cannot be computed because at least one of the variables is constant.

Figure 5.37 indicates that the highest wind speed during summer months (DJF), with least frequency of wind blowing from the south-east at wind speeds ranging from 6-50.4 m/s¹ 10% of the time. The autumn (MAM), winter (JJA) and spring (SON) months ranged from 6-50.4 m/s¹, with the same northerly winds over the months for 100% of the time. The calmness of the wind was 0% throughout the seasons.

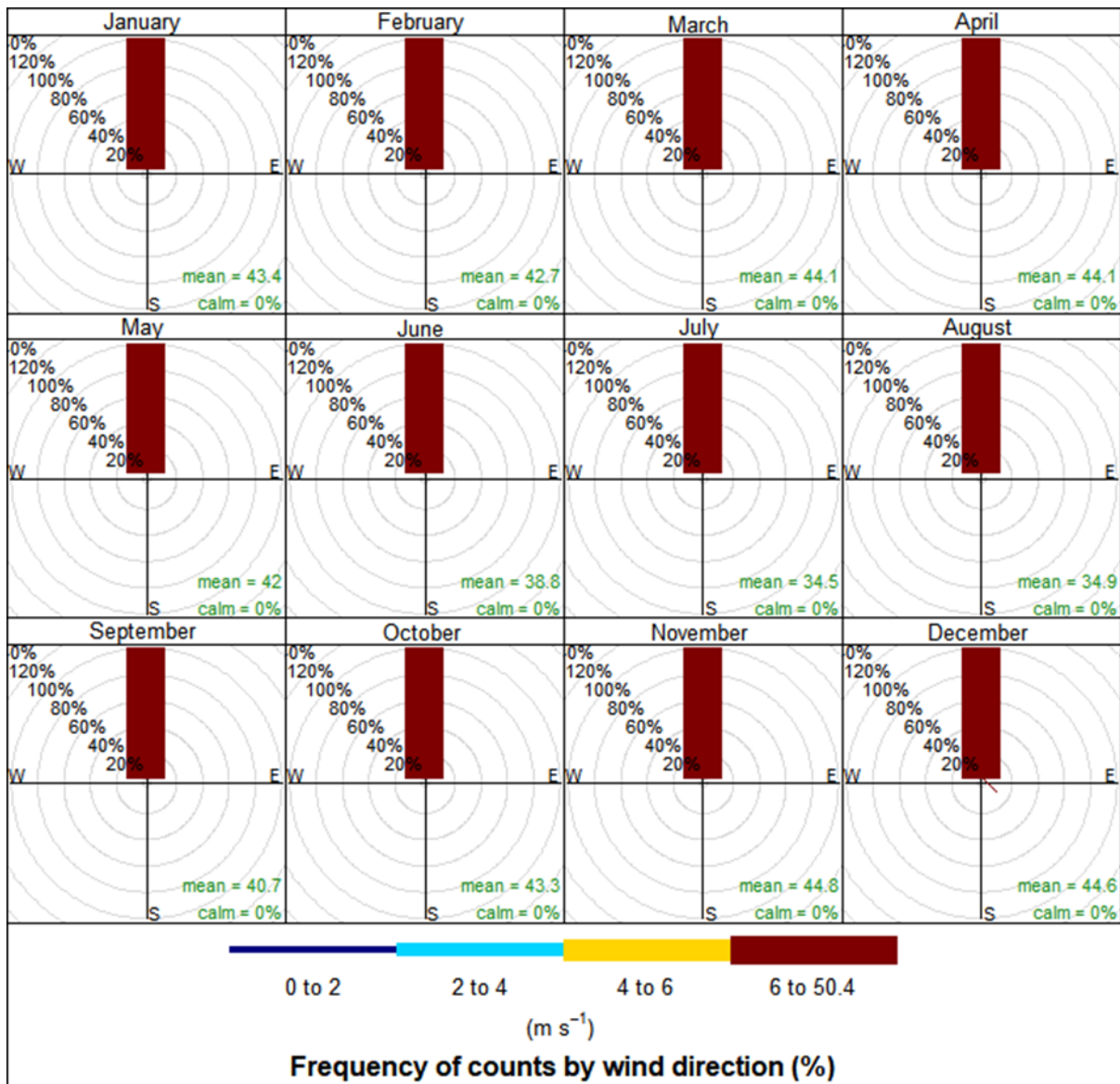


Figure 5.37 Wind roses for the Pietermaritzburg Airport

5.4 Proposed EThAQI and MsuAQI

Due to the number of high exceedances observed in the study area, a collective Air Quality Index has been proposed to clearly illustrate health risks associated with the dominant air pollutants per area. The proposed dual Air Quality Index is based on the WHO sub-descriptor (Good) and local NAAQS (Moderate-Hazardous).

Table 5.8 Proposed breaking points for different pollutants

Descriptor	AQI	PM ₁₀ µg/m ³ (24hr)	PM _{2.5} µg/m ³ (24hr)	SO ₂ ppb(24hr)	NO ₂ ppb(1hr)	O ₃ ppb(8hr)
Good	0-50	0-45	0-15	0-15	0-53	0-13
Moderate	51-100	46-120	16-65	15-48	54-106	14-41
Unhealthy for sensitive group	101-150	121-140	66-85	49-68	107-159	42-68
Unhealthy	151-200	141-160	86-105	69-88	160-212	69-95
Very unhealthy	201-300	161-180	106-125	89-108	213-264	96-122
Hazardous	301-500	>181	>126	>109	>265	>123

Based on the proposed eThAQI, a moderate (51-100) AQI was observed during the summer, with a maximum of 52. PM_{2.5} was the most dominant pollutant during this period. In autumn, the observed AQI was moderate, with a maximum of 75, and PM_{2.5} was dominant. In spring, the maximum AQI observed was 100, with PM_{2.5} being the dominant pollutant. In winter, observed AQI was unhealthy (151-200); the maximum AQI was 182, which is shown in the monthly variation in July, and PM₁₀ as the dominant pollutant during this period (refer to Figure 5.38).

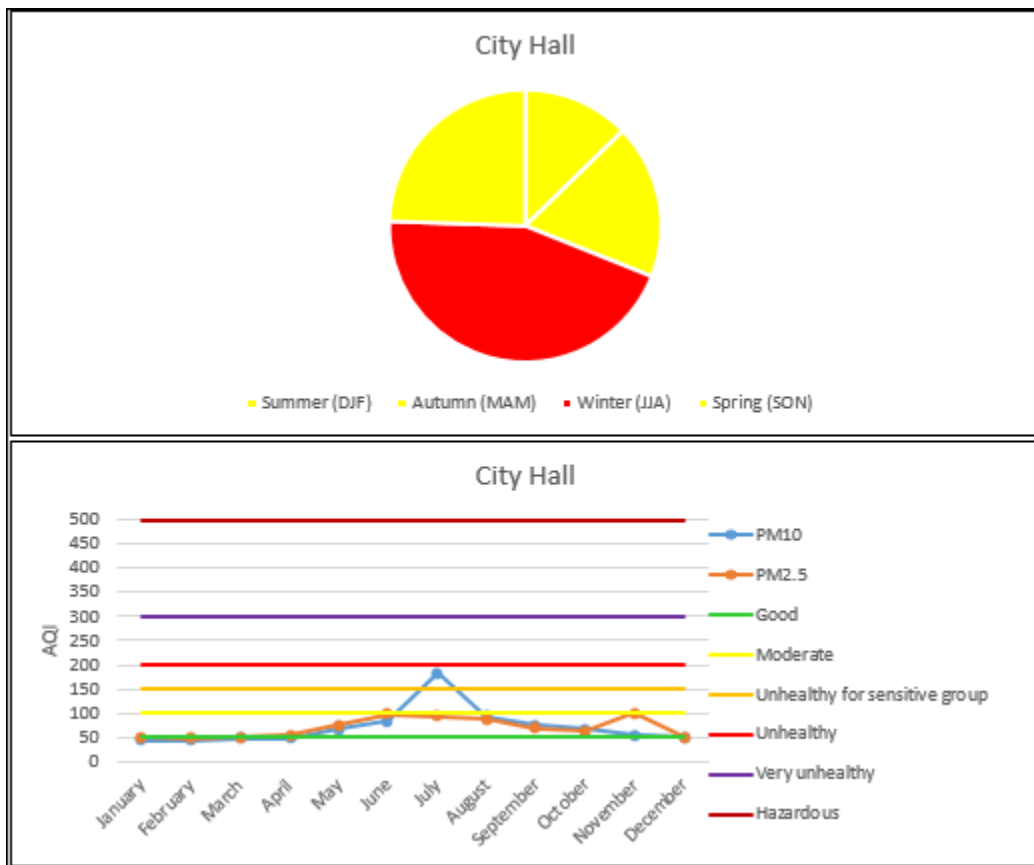


Figure 5.38 City Hall seasonal AQI pie-chart and monthly variation AQI

Based on the proposed eThAQI, a moderate (51-100) AQI was observed during the summer with a maximum of 89, with SO₂ being the dominant pollutant. In autumn, the maximum observed AQI was 83, with PM_{2.5} being dominant. During spring, the maximum AQI observed was 80, with PM₁₀ being the dominant pollutant. In winter, observed AQI was hazardous (301-500), with a maximum of 326 being recorded in July, and with PM_{2.5} being the dominant pollutant during this period (refer to Figure 5.39).

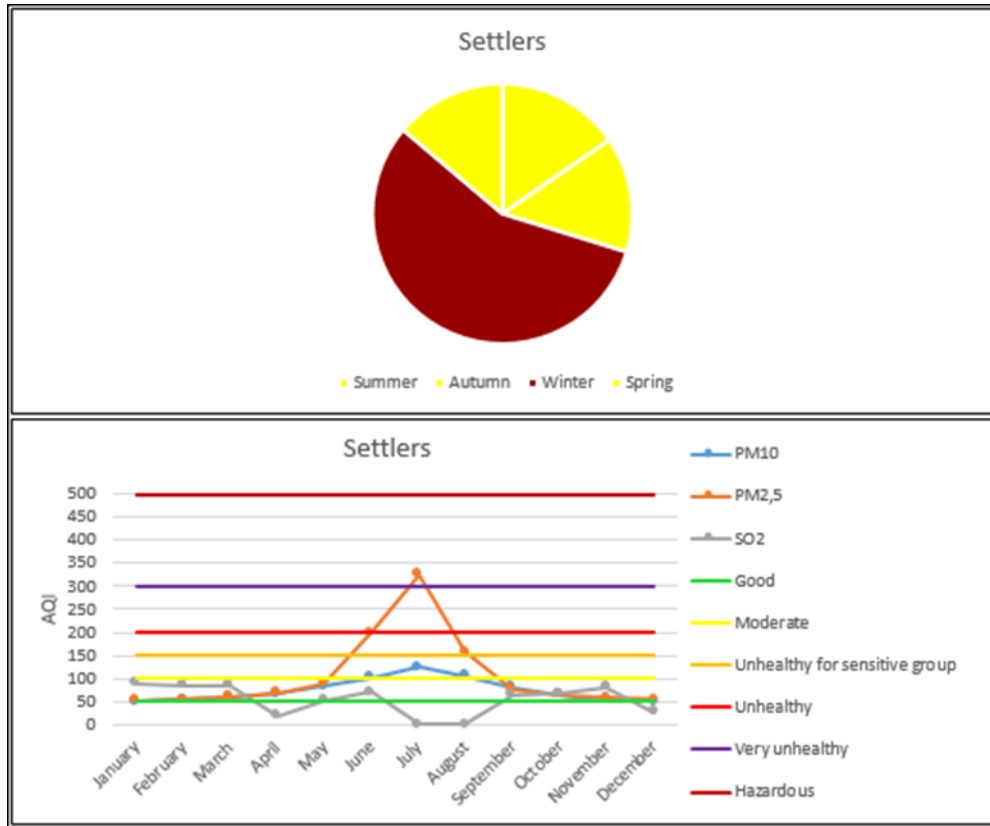


Figure 5.39 Settlers seasonal AQI pie-chart and monthly variation AQI

Based on the proposed eThAQI, a moderate (51-100) AQI was observed during the summer, with a maximum of 63, and SO₂ was the dominant pollutant during this period. In autumn, the maximum observed AQI was 84, with PM_{2.5} being dominant. In spring, the maximum AQI observed was 75, with PM₁₀ being the dominant pollutant. In winter, the observed AQI was very unhealthy (201-300), with a maximum AQI of 226 being observed in June and July, and PM_{2.5} was the dominant pollutant during this period (refer to Figure 5.40).

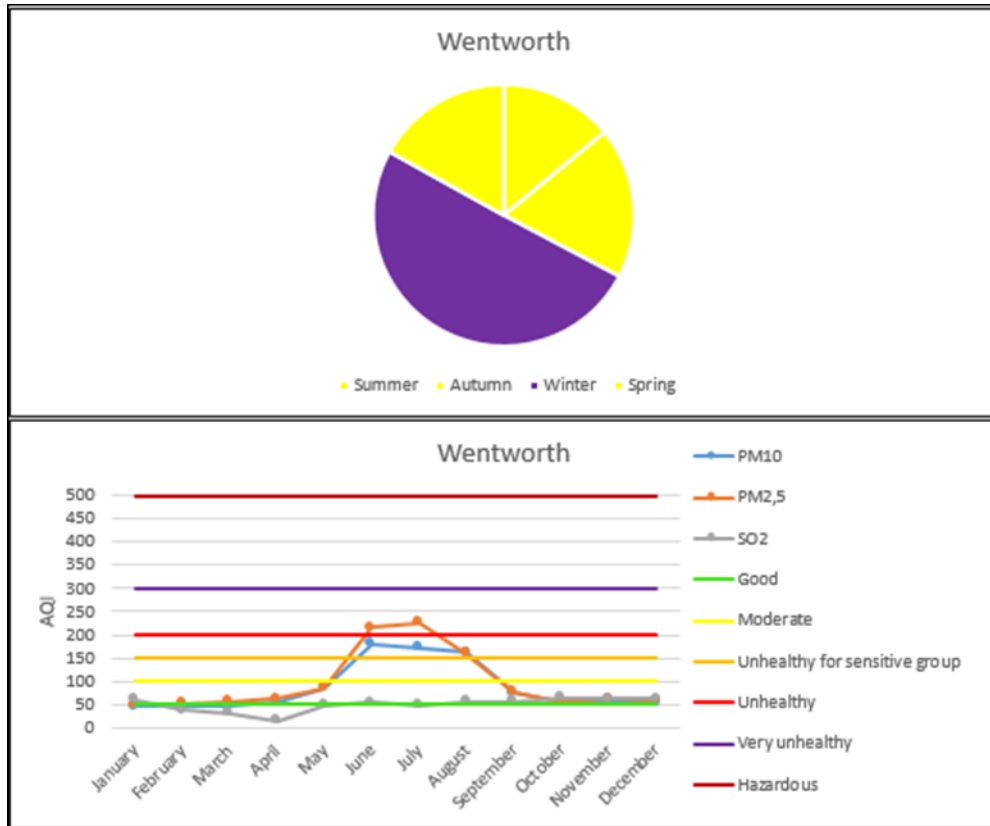


Figure 5.40 Wentworth seasonal AQI pie-chart and monthly variation AQI

Based on the proposed eThAQI, a good (0-50) AQI was observed during the summer, with a maximum of 16, in autumn the maximum observed AQI was 24, and in spring the maximum AQI observed was 13. In winter, the observed AQI was hazardous (301-500), with a maximum AQI of 409 being observed in July (refer to Figure 5.41).

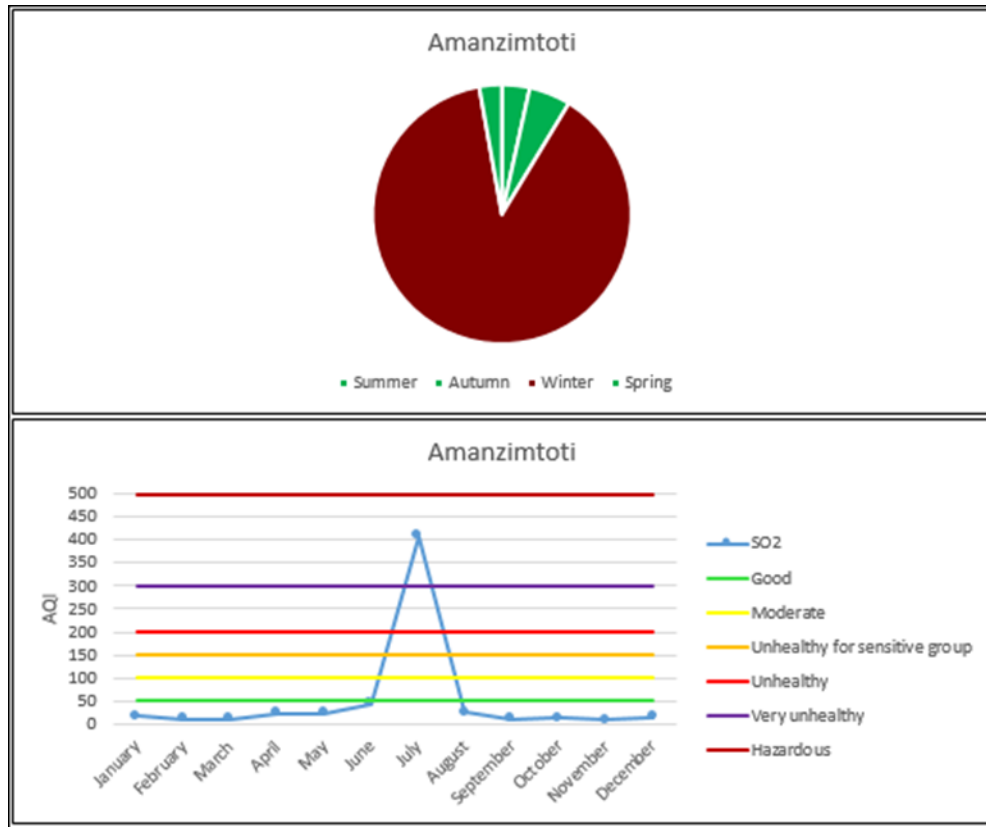


Figure 5.41 Amanzimtoti seasonal AQI pie-chart and monthly variation AQI

Based on the proposed eThAQI, in summer, autumn and spring, the maximum observed AQI was moderate at 65, 64 and 55, respectively. In winter, the observed AQI was unhealthy for sensitive groups (101-150) in June and July, when the maximum AQI was 138. NO₂ was the dominant pollutant during the study period (refer to Figure 5.42).

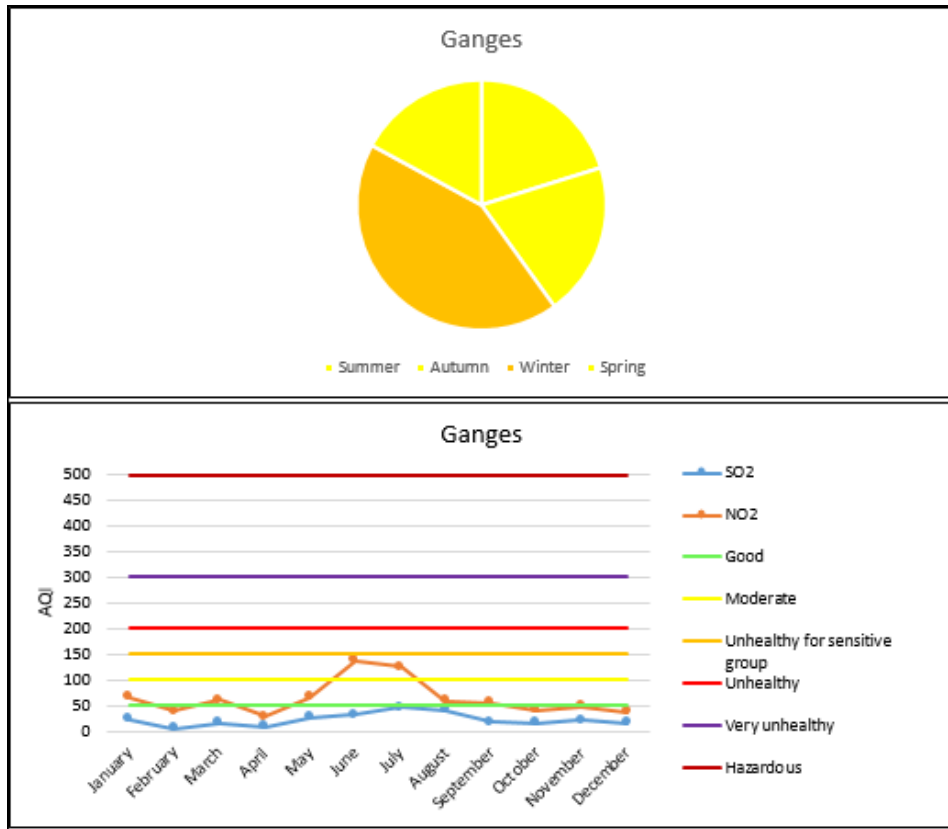


Figure 5.42 Ganges seasonal AQI pie-chart and monthly variation AQI

Based on the proposed eThAQI, a moderate (51-100) AQI was observed during the summer, with a maximum of 95. In the winter and spring, the observed AQI was unhealthy for sensitive groups (101-150), with the maximum being 119 in July and 121 in November (refer to Figure 5.43).

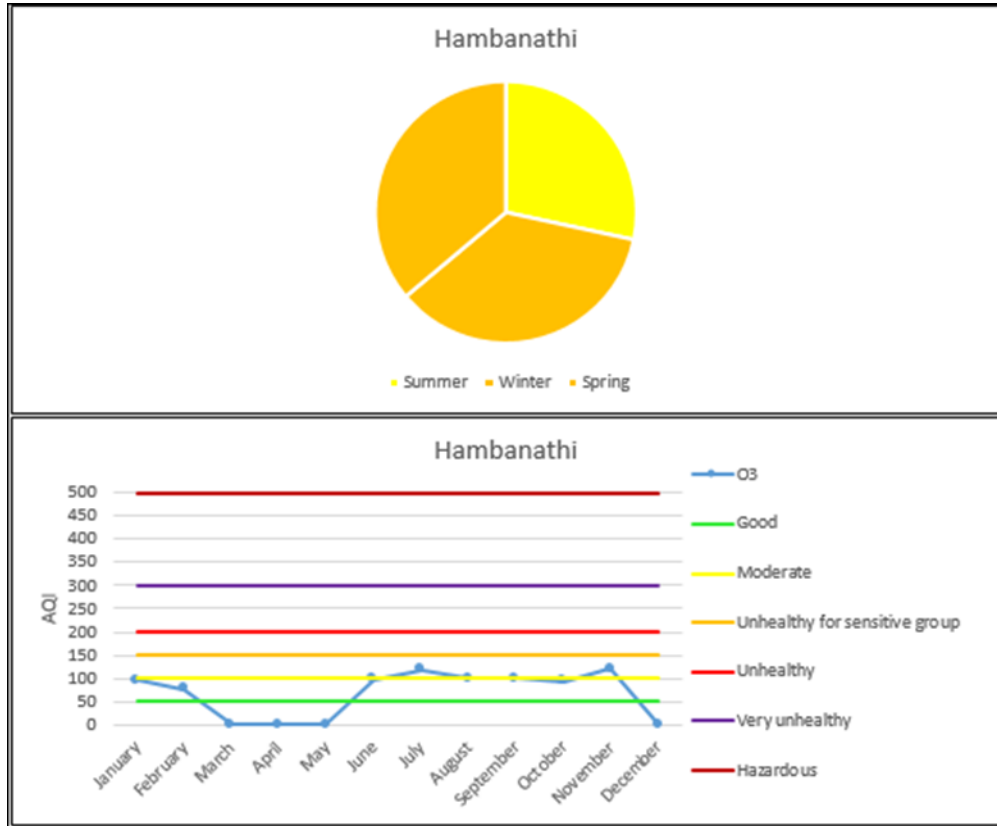


Figure 5.43 Hambanathi seasonal AQI pie-chart and monthly variation AQI

Based on the proposed MsuAQI, a moderate (51-100) AQI was observed during the summer, with a maximum of 75. In autumn, the maximum AQI was 81, and in winter (July) it was 82, while it was 80 in spring. SO₂ was the dominant pollutant in all the seasons (refer to Figure 5.44).

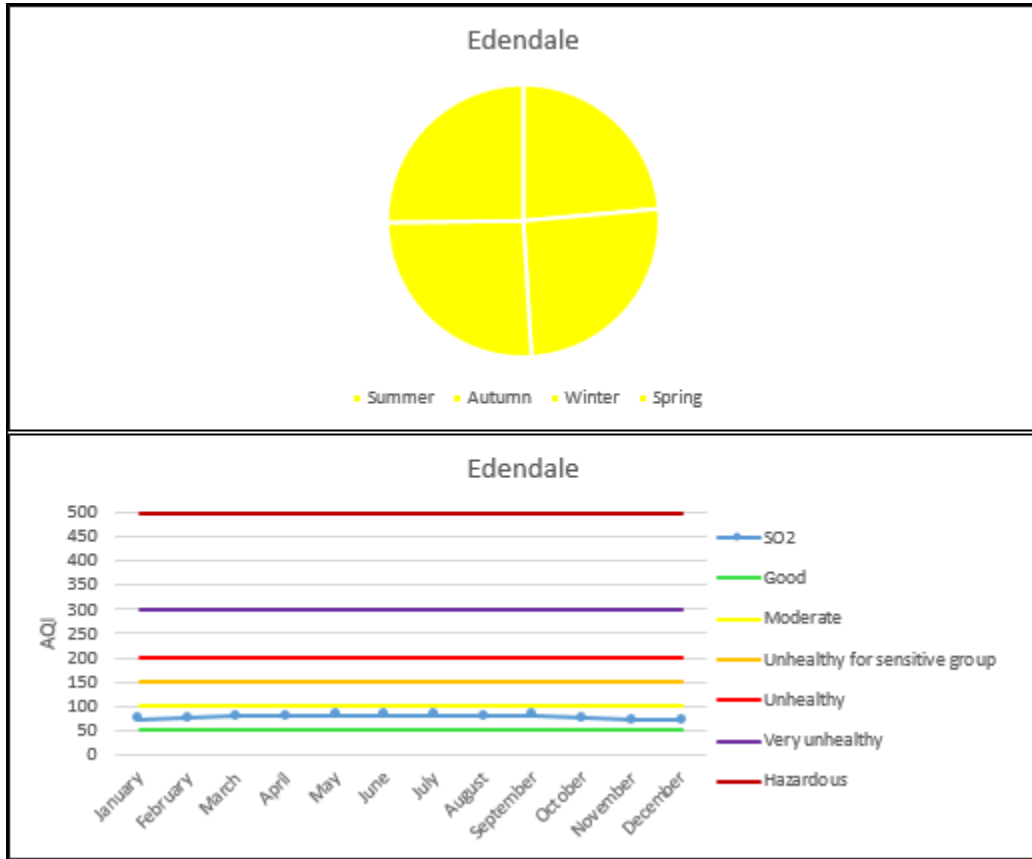


Figure 5.44 Edendale seasonal AQI pie-chart and monthly variation AQI

The proposed AQI was observed to be hazardous (301-500) during summer, with a maximum of 477 in January. PM_{2.5} was dominant pollutant during this period. The AQI was observed to be moderate (51-100) in autumn, with a maximum of 63 and with PM₁₀ being dominant. In winter, the maximum observed AQI was 73 (SO₂) and in the spring, the maximum was 77 with SO₂ (refer to Figure 5.45).

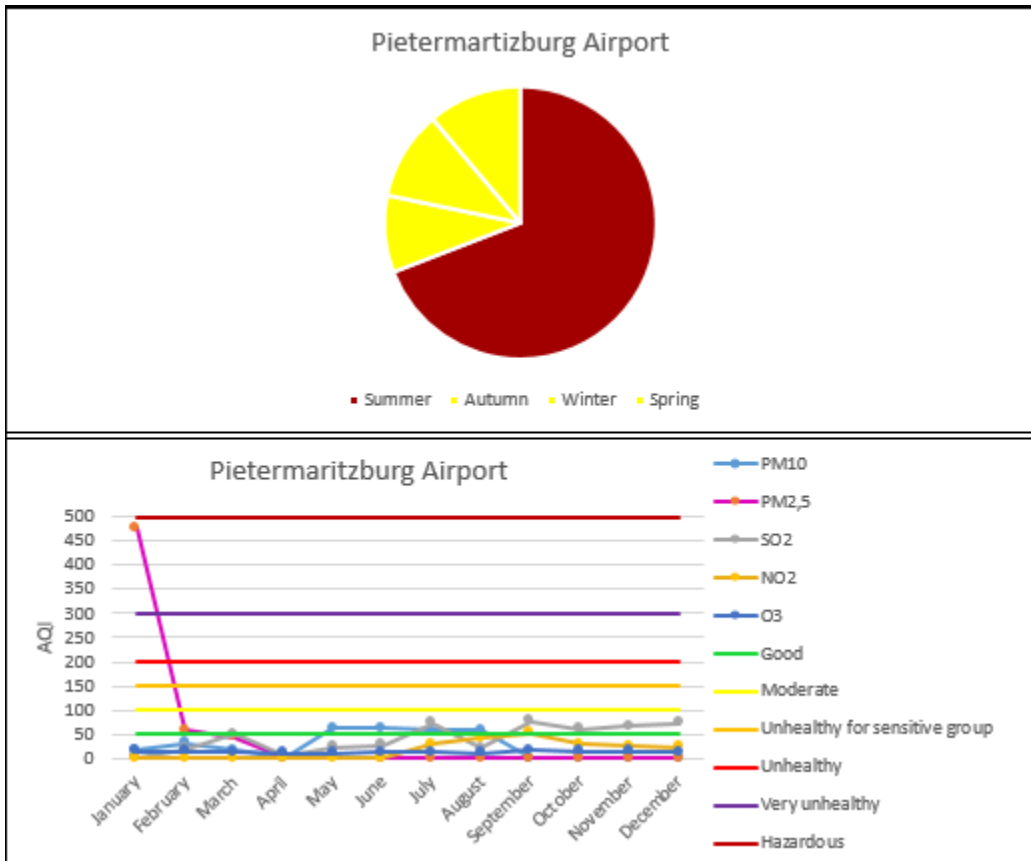


Figure 5.45 Pietermaritzburg Airport seasonal AQI pie-chart and monthly variation AQI

The proposed AQI was observed to be good (0-50) during the summer, with a maximum of 25 and with SO₂ being the dominant pollutant during this period. In autumn, the maximum observed AQI was 17, with SO₂ being the dominant pollutant, in winter the maximum was 42, with SO₂ being the dominant pollutant, and in spring, the observed AQI was hazardous (301-500), with a maximum of 500 in September and with NO₂ being dominant (refer to Figure 5.46).

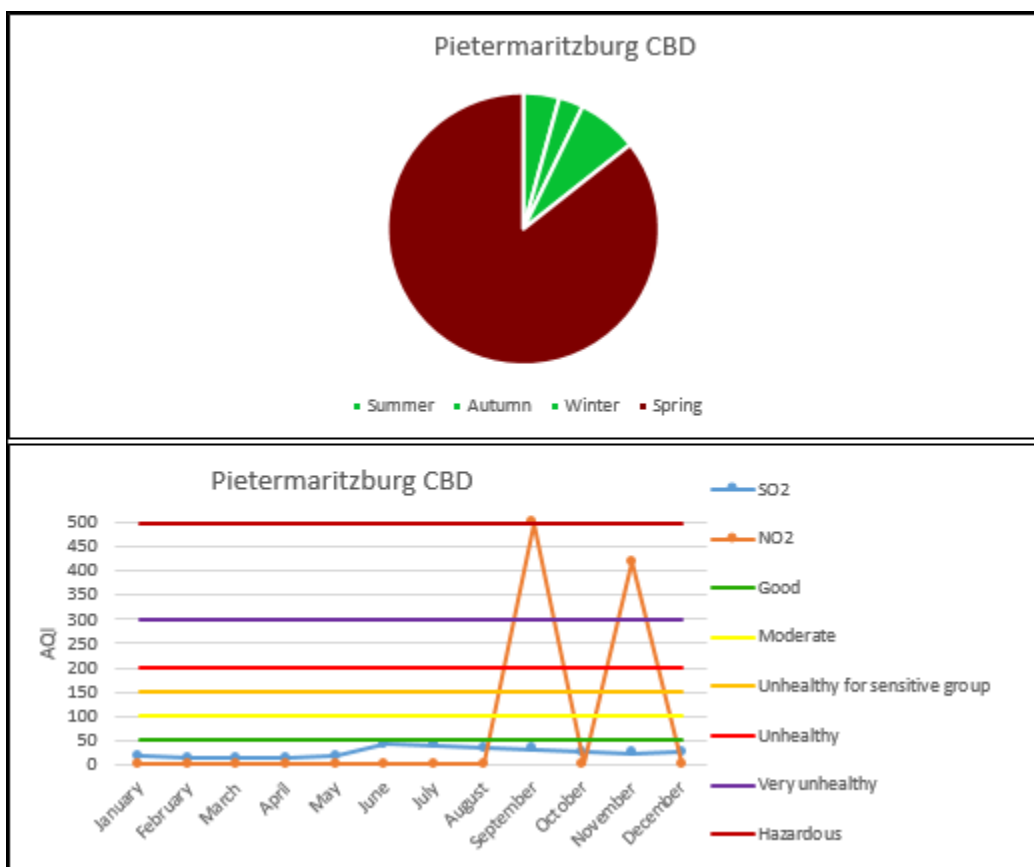


Figure 5.46 Pietermaritzburg CBD seasonal AQI pie-chart and monthly variation AQI

5.5 Conclusion

This chapter presented the findings of the study from the analysed data. It describes the state of air quality by analysing the concentrations of pollutants and pollutants, using World Health Organization guidelines and national ambient air quality standards as its thresholds. This chapter shows the spatial distribution of air pollutants, and literature shows that air pollutants have a relationship with weather parameters, so the chapter also determines the relationship between air pollutants and weather conditions. Finally, a proposed eThekweni and Msunduzi Air Quality Index was developed, which uses both the WHO and NAAQS as its threshold, since the literature has indicated that even a low concentration of air pollutants, such as PM_{2.5}, can have an impact on human health, especially for those living with pre-existing medical conditions, those who are elderly, as well as children.

CHAPTER SIX

DISCUSSION, CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This chapter summarizes the results of descriptive analysis and the exceedances that were recorded by the stations, which show that people within the eThekweni and Msunduzi Municipalities are breathing in air with a high concentration of air pollutants that exceed the local (NAAQS) and international (WHO) thresholds. A spatial analysis was conducted by using the GIS kriging tool to determine the distribution of these air pollutants. A linear correlation between air pollutants and meteorological conditions was determined and will be discussed further in this chapter, as well as the status of the proposed AQI. This chapter also includes what other researchers have found with regard to the findings on this study, and it includes the conclusion and recommendations.

6.2 Discussion

6.2.1 Exceedances and spatial distribution of the air pollutants

This analysis demonstrates that the dataset remained spread out and that some of it was distributed around the mean. The datasets that were selected for the study had a data recovery rate of 80% and upwards. A positive skewness of the data was observed in all the air quality monitoring stations, which indicates that the air pollutants being emitted within the study area had higher values at some intervals throughout the day, during the study period. All stations with a recovery rate higher than 80% were then selected and exceedance graphs were constructed. The results of the exceedance study clearly indicated that most of the air pollutants being emitted exceeded those of the WHO and NAAQS thresholds, especially for PM_{2.5} and PM₁₀. The PM_{2.5} recorded at the City Hall, Settlers, Wentworth and the Pietermaritzburg Airport exceeded both the WHO and NAAQS standards, but only PM₁₀ exceeded the WHO guidelines throughout the study period, mostly during the winter period, this was due to emission from domestic sources (burning of coal/wood for cooking or space heating), vehicles, industries. These high exceedances observed during the winter period might be due to a surface temperature inversion layer that traps the emitted air pollutants on the earth's surface. A surface temperature inversion layer forms when the sky is clear, when there are calm winds and long nights, and when the warm air above acts as a lid and keeps the cool air on the ground. This usually occurs during the winter season (Johnson, 2018; Trinh et al., 2018).

High exceedances of SO₂ were observed at Amanzimtoti and in the Pietermaritzburg CBD, the high quantities of SO₂ in the air can be caused by a variety of human activities (emissions from industries, biomass burning, vehicles, and chemical processes) and natural phenomena (temperature inversion).

Exposure to these pollutants is linked to lung cancer, asthma, rhinitis, heart disease, and other respiratory diseases. In a study conducted by Kaniabadi et al. (2017) in Iran, Kermanshah is considered one of Iran's largest contaminated cities due to the presence of several major industrial plants and the presence of a large number of automobiles. It was found that mortality rate increased due to high levels of PM₁₀ and increased days exposure to these pollutants (Kaniabadi et al., 2017). A study by Kistnasamy (2008) found that the SO₂ and PM₁₀ concentrations fell below both the international and South African standards and guidelines. School children exposed to these pollutants reported an increase in respiratory symptoms such as cough, wheezing, chest inflammation, fatigue, and respiratory failure. Spatial distribution of these pollutants in the eThekweni Municipality showed a higher concentration in the south of Durban due to emission sources such as emissions from vehicles, industries, biomass burning, compared to the north. The concentration of air pollutants in the Msunduzi Municipality was quite high along the eastern side of the research area, which was attributable to the near proximity of the emission sources to the monitoring stations, as well as meteorological characteristics that contributed to the high pollutants.

6.2.2 Linear Correlation between Air Pollutants and Meteorological Factors

The relationship between air pollutants and meteorological parameters is complex, with variations depending on local conditions, emission sources, and atmospheric processes. Understanding these linkages is critical to air quality monitoring, forecasting, and pollution management activities. During the spring, the relationship between PM_{2.5} and PM₁₀ and the wind speed/direction was positive, weak and significant, this means the variable are correlated in the same direction that is positive, but their relationship is least than 50 % as in weak however weak as it may be but when testing the relation, it was found to be significant. The correlation with the temperature was positive in summer and autumn, and in winter it was negative and significant, which means that if the temperature decreases, then the particulate matter increases. The correlation with the relative humidity was positive in some stations and negative in others, which might be due to their geographical locations.

The findings of the study indicate a positive linear correlation between O₃ and temperature during the seasons. These results show that the environment and temperature play an important role in O₃ concentration. A study by Abdullah et al. (2016) found that the daily temperature and the daily concentration of O₃ have a positive linear relationship in Terengganu. This is supported by Lee et al. (2013), who also found that the ground ozone is sensitive to temperature. Wind speed and wind direction had negative and significant relationship with O₃ across all seasons, while the relative humidity and O₃ had a negative and significant relationship throughout the seasons. O₃ is dependent on temperature and other primary air pollutants, such as NO₂.

The linear correlation between SO₂, the wind speed and wind direction varied across the stations. It was found to be positive, weak and significant during the summer, autumn and spring. In winter, the relationship was positive, weak and significant in most of the stations, but in Amanzimtoti the relationship was positive, relatively strong and significant, which means that SO₂ is dependent on wind speed and wind direction. Diab et al. (2002) discovered a strong and positive relationship between SO₂ and the wind speed. Correlation between SO₂ and the temperature was negative in most stations in summer, but a positive relationship was recorded at Pietermaritzburg Airport. In autumn, the relationship was positive at the Amanzimtoti and Wentworth stations, while a negative non-significance was observed in the Pietermaritzburg CBD and at the Airport. In spring, a positive relationship was observed in most stations between SO₂ and the temperature, except at the Amanzimtoti and Edendale stations, where the relationship was negative. The correlation between SO₂ and the relative humidity was positive for most stations throughout the seasons, although a negative relationship was observed in autumn, winter and spring. These findings show that SO₂ concentrations are influenced by the meteorological conditions, but mostly by the emission activities within the municipalities. Kalbarcyk et al. (2019) found that SO₂ concentration was significantly dependent on the meteorological conditions; they estimated that it was approximately 9% in summer and 38% in winter.

The linear correlation between NO₂, wind speed and wind direction were found to be negative in the Pietermaritzburg CBD and positive at Pietermaritzburg Airport during summer; however, the relationship was negative during the winter and positive during spring. A study by Liu et al. (2020) found that NO₂ and wind speed have a negative relationship. The temperature and NO₂ concentration were negative at the Pietermaritzburg Airport during summer, winter and spring, which shows that NO₂ has no effect or no relationship with temperature and are mutual exclusive

is not dependent on the temperature at this site, but that the emission activities are influencing the concentration levels. The relationship was positive in the Pietermaritzburg CBD, although it was weak and non-significant during the winter. This observation shows that this relationship is unlikely to occur as it is also being influenced by nearby activities, such as vehicle emissions. The correlation between NO₂ and the relative humidity was positive throughout the seasons and a negative relationship was observed in the Pietermaritzburg CBD during the spring. According to Liu et al. (2017), temperatures and wind speed showed negative correlation coefficients, and relative humidity showed positive correlation coefficients.

The results from the wind roses in the eThekweni Municipality showed that the Amanzimtoti station was receiving south-westerly prevailing winds in all the seasons. At Hambanathi, north-easterly winds prevailed, although the data were limited. At Wentworth, north-easterly winds prevailed in summer, autumn and winter seasons, and in spring prevailing winds were from the south. The Msunduzi Municipality results showed that the Edendale station receiving easterly winds in summer, autumn and spring, and the station received south-westerly winds in winter. Both Pietermaritzburg Airport and Pietermaritzburg CBD received winds from the north in all the seasons.

6.2.3 AQI status in the eThekweni and Msunduzi Municipalities

The results of the proposed AQI showed that most of the people living in eThekweni, especially those living in the south of Durban, were exposed to high concentrations of PM₁₀, PM_{2.5} and SO₂ during the winter season, this is due to a combination of industrial activity, increased energy consumption, bad weather conditions, and limited dispersion might result in high levels of PM₁₀, PM_{2.5}, and SO₂ in industrialized areas during the winter months, resulting to raised AQI values and potential health implications on people; hence it proposed a combined AQI that is based on the WHO and NAAQS, in order to reduce the health risks that are reported to be harmful to health and well-being of people living there. The main emission sources that were identified at the City Hall were vehicle emissions i.e. on the M4 at Settlers, there were industrial emissions from, for example, Sapref (the largest crude oil refinery in southern Africa), as well as the Mondi Merebank paper mill, the Isegen manufacturer of food acidulants and the Engen refinery, as well as combustion of biomass fuel for cooking and space heating, and vehicle emissions. At Amanzimtoti, the emission sources were identified to be vehicle emissions i.e. the N2 highway and the R102, industrial emissions i.e. the Southgate industrial park (Prince Minerals - a chemical manufacturer,

Toyota Boshoku SA - a car manufacturer, and YARA SA Pty - an animal nutrition manufacturer). The emission sources that were identified at Wentworth were industrial emissions i.e. Isoko Petroleum, the Safripol refinery, LCS logistics company, domestic emissions for cooking and space heating, as well as vehicle emissions i.e. along the M4 highway.

The results of the proposed AQI in the Msunduzi Municipality were observed, in most cases, to be moderate throughout all seasons. There were two cases where the AQI recorded hazardous contamination levels, namely, in the Pietermaritzburg CBD and at the Pietermaritzburg Airport during the spring and summer, respectively. According to the proposed AQI, the most dominant air pollutants are NO₂ and SO₂, which indicates that during the spring and summer seasons of the study period both the sensitive group and the general population were exposed to unhealthy levels of these air pollutant concentrations. This high concentration of these pollutants is due to the geographical features of industrialized areas, such as valleys or basins, which can increase air pollution by trapping pollutants in the surrounding area. Furthermore, the Msunduzi Municipality consist of a number of sugar cane farms therefore sugarcane harvest season can considerably raise air pollution levels in affected areas, posing environmental and health dangers to adjacent residents. In addition, the main identified emission sources at Edendale and the Pietermaritzburg Airport are industrial emissions i.e. FF refineries, an oil and natural gas company, LAFARGE, a concrete manufacturer, sugar cane farming, domestic fuel burning for cooking and heating and vehicle emissions i.e. along the M70 highway. The emission sources in the Pietermaritzburg CBD were identified to be from vehicle emissions i.e. the R103 and the N3, as well as landfill emissions i.e. the New England Road landfill site, and domestic fuel burning for cooking and space heating.

The dominating air pollutants within the municipalities are very detrimental to human health, and to the environment as a whole. A study conducted by Gray (2019) in Highveld priority area studied air quality impact and health impacts of large stationary emission sources and found that ambient particulate matter was responsible for 305-650 of early deaths in 2016. Furthermore, a study by Luo et al. (2016) found that the daily mean increases of 10 µg/m³ in the NO₂ concentration were linked with a surge in the total daily cardiovascular, cerebrovascular and ischemic heart disease mortality. In Beijing, Han et al. (2017) found that exposure to NO₂ is linked with allergic airway inflammation and increases the vulnerability to asthma. An analysis of Orellano et al. (2021) found that short-term exposure to SO₂ was associated with the death rate of all causes and respiratory infections.

6.3 Conclusion

Many people living in eThekweni and Msunduzi municipalities may be breathing unhealthy air, especially those living in areas where industries are nearby and live near a highway. The study's findings show that the constitutional right of an environment that does not affect the health and well-being of the population is being violated in these municipalities as they are exposed to high concentrations of air pollutants. According to the National Environmental Management Air Quality Act, Section 8(a) states that local authorities are required to observe outdoor air quality and emissions from point, non-point and mobile sources. For years, studies have been reporting unprecedented air pollution levels especially south of Durban, and it is still an ongoing problem, especially when it comes to pollutants, such as particulate matter.

Consequently, municipal-based tools, such as the AQI, can inform the public during high-emission episodes, and municipal authorities must ensure that municipal regulations are structured so that they can include small-scale emissions not regulated by atmospheric emissions permits, that they make a list of the controlled emitters and controlled fuels, as well as a list of a range of new criminal offences. In addition, they need to review their existing licenses and emission reports to ensure that the big industries, which are regulated by the atmospheric emission licenses, comply with them. This study proposed that an AQI should be made up of stricter breaking points. The literature reported that respiratory illnesses have been observed among the public who live near industries, landfill sites and roads with heavy traffic. The proposed AQI will be used as an early warning tool to assist the communities and to advise them on what to do in the case of high concentrations of air pollutants, especially during the winter, when temperature inversion is at its strongest and when there is a high concentration of pollutants.

6.4 Recommendations

Municipalities should ensure that air quality monitoring stations are appropriately calibrated at all times to achieve data recovery rates of at least 80%, especially in the eThekweni municipality, and more air quality monitoring stations in the Msunduzi municipality are required for better coverage throughout the municipality. A major reduction in ambient particulate matter emissions is necessary in the eThekweni Municipality, as well as the reduction of NO₂ and SO₂ emissions in the Msunduzi Municipality. Air pollution has no boundaries; it can travel to areas far away from its

emission source. It not only affects human health, but also the environment i.e. the water resources (acid rain) and soil (soil acidity). Therefore, a collective approach is recommended to ensure that the public is not exposed to harmful chemicals released to the air and ensure that a reduction in emissions is achieved. It is essential for individuals to know the status of the air that they breathe, and therefore, it is recommended that they have an educational awareness of air quality status, by using tools such as the AQI. More studies should be conducted to try and bridge the knowledge gap regarding the health impact of air pollution, especially since we have recently experienced a pandemic, which affects the respiratory system. Therefore, it is recommended that more studies should include impact of air pollution on COVID19 cases within these municipalities. It is also recommended that they ensure that all the industries within their boundaries are reporting their air emissions to National Atmospheric Emissions Inventory System (NAEIS), as stated on their Atmospheric Emission License (AEL). A fine should be enforced on all industries that do not comply with their AEL.

CHAPTER SEVEN

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