**UNIVERSITY OF KWAZULU-NATAL**

**Study on Sulphur Dioxide ($SO_2$) and Particulate Matter 10 ($PM_{10}$) variations in the City of Tshwane, Gauteng.**

**By**


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**PREFACE**

The research contained in this dissertation/thesis was completed by the candidate while based in the Discipline of Environmental Science, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Westville Campus, South Africa. The research was financially supported by my spouse.

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 caused by investigations by the candidate.

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Signed:

Date: 18 August 2021

**DECLARATION 1: PLAGIARISM**

I, Ayanda Matyeni, declare that:

i. The research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

ii. This dissertation has not been submitted in whole or in part for any degree/ examination to any other university;

iii. This dissertation does not contain other persons' data, pictures, graphs or additional information unless expressly acknowledged as being sourced from other persons;

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(v) Where I have used material for which publications followed, I have indicated in detail my role in the work;

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## ABSTRACT

Air pollution is a global concern caused by road and air traffic, the rapid growth of the industrial sector, and urban development. About 3.7 million people annually die prematurely, globally caused by air pollution. Air pollution also destroys the crops that would have been enough to feed millions of people. The World Health Organization (WHO) recently reported an alarming 80% of urban area dwellers in selected areas breathing air laden with pollutant levels above the set standards (WHO, 2016).

South Africa established a database of regions that tracks air pollution levels. As of 2013, there were reports that the greater Johannesburg / Gauteng region had the most polluted air in the country. In 2016, the Hartbeespoort area was added to the database, due to it's highly polluted air because of its proximity to major industrial areas.

Air quality in the City of Tshwane, situated in Gauteng Province, is also influenced by its location as it is close to the industrial areas of Johannesburg. Globally, the city was the 162nd most air-polluted area, with a particulate matter concentration of 60 mg/m$^3$. Mining operations and other industries, vehicle emissions, domestic fuel burning, and veld fires are among the sources of poor air quality in the Gauteng province. Gauteng is also one of the most densely populated areas, with heavy traffic and informal settlements using coal or other fuel fires also adding to the air pollution.

This research aimed to examine the significant air pollutants in Tshwane, Gauteng, and the resulting air quality. Pollutants of concern in this study were sulphur dioxide ($SO_2$) and particulate matter ($PM_{10}$). The study focused on temporal variations of the concentrations of the major pollutants at the continuous air quality monitoring stations. Furthermore, the focus was on how the concentrations of the pollutants influence the quality of the environment and human health. Sampling took place at various areas in the City of Tshwane, and the results were compared to the WHO standards for air quality.

It was found that solutions to the air pollution problems exist, including better and simpler methods for starting coal fires, broader electrification, cleaner stoves and chimneys, increased ventilation, and the use of low-smoke fuels, less production of carbon dioxide, and overall improvements in technology.

**ACKNOWLEDGEMENTS**

This period has been a phase of intense learning for me in the scientific arena and personally. I want to reflect on the people who have given me support and helped me throughout this period in my life.

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**List of Acronyms**

AERONET ........................................................................................ Aerosol Robotic Network
APPA.........................................................................................Air Pollution Prevention Act
AQA ............................................................................................................Air Quality Act
AQMP .............................................................................................Air Quality Management Plan
CBD...................................................................................................Central Business District
CFCs........................................................................................................ Chlorofluorocarbons
$CH_4$ ............................................................................................................................Methane
CO .............................................................................................................Carbon Monoxide
$CO_2$.................................................................................................................Carbon dioxide
CoT.................................................................................................................City of Tshwane
CoTMM................................................................ City of Tshwane Metropolitan Municipality
$C_6H_6$..............................................................................................................................Benzene
DEA....................................................................... Department of Environmental Affairs
NEMAQA .............................................National Environmental Management Air Quality Act
NO ..........................................................................................................................Nitric oxide
$NO_2$............................................................................................................ Nitrogen Dioxide
$O_3$.......................................................................................................................................... Ozone
NOx .............................................................................................................Oxides of nitrogen
Pb.......................................................................................................................................Lead
PM ........................................................................................................Particulate matter
$PM_{2.5}$...................................................................... Particulate matter with a diameter < 2.5 µm
$PM_{10}$ ...................................................................... Particulate matter with a diameter < 10 µm
Ppb....................................................................................................... Parts per billion
Ppm.......................................................................................................Parts per million
SANAS............................................................... South African National Accreditation System
SANS……………………………………………………….South African National Standards
SAWS.............................................................................South African Weather Services
$SO_2$ ..........................................................................................................Sulphur Dioxide
VOCs.................................................................................Volatile organic compounds
WHO ..................................................................................World Health Organization

# CHAPTER 1: INTRODUCTION

## 1.1 Rationale for the Research (Nature and Scope)

The City of Tshwane is located in the Province of Gauteng and is the second-largest municipality in that province. The city is one of the six metropolitan regions in South Africa (Liebenberg-Enslin & Petzer, 2005). The geographical coordinates for the City of Tshwane are 25.6051° S, 28.3929° E. The area under investigation is approximately 85.5 km north of Johannesburg and 132.7 km from Emalahleni (Thamm, 1998).

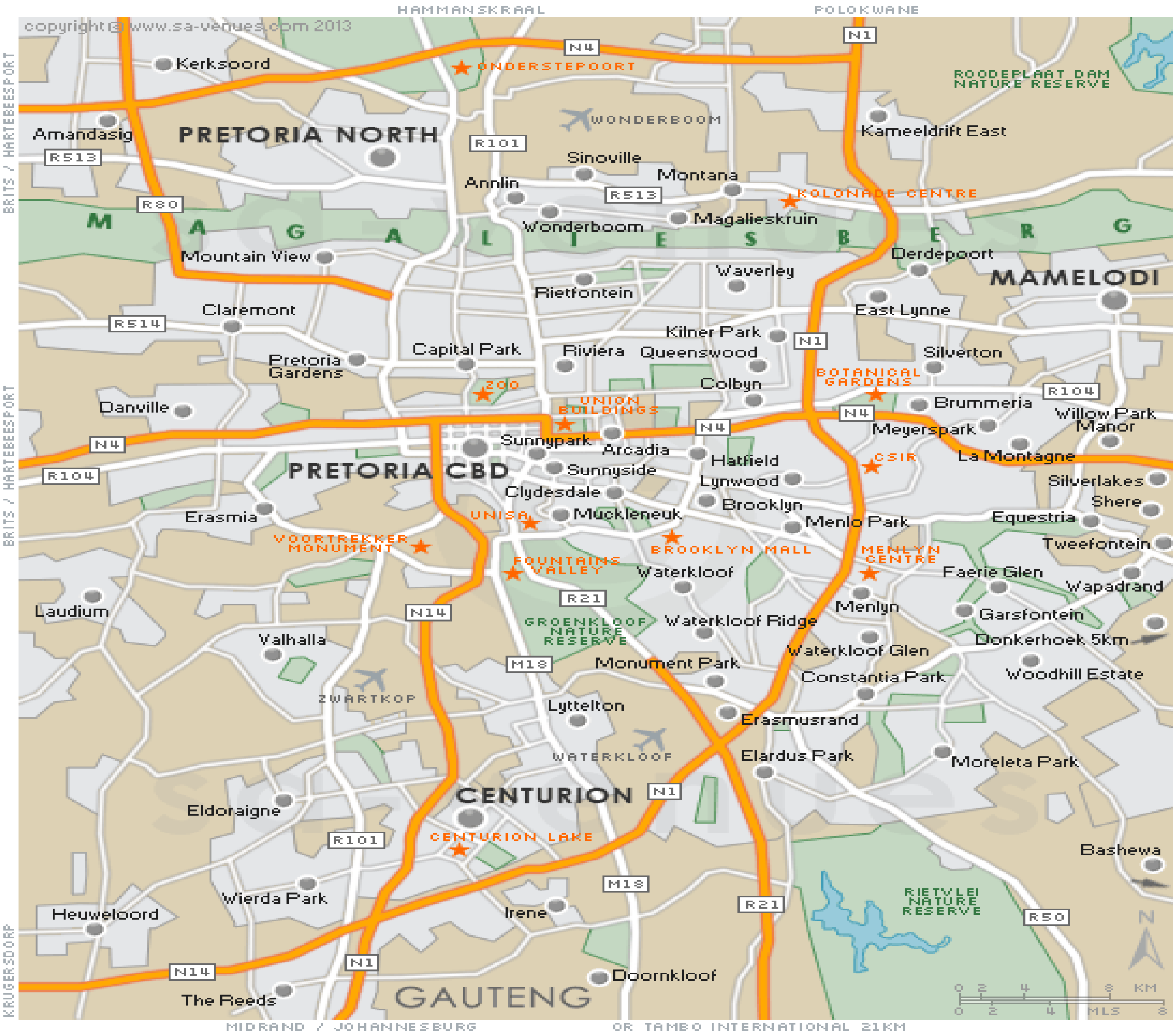



**Figure 1.1: Map of the City of Tshwane (sourced from https://www.sa venues.com/maps/gauteng_pretoria.htm)**

Many residential and industrial developments have occurred within the illustrated area and surrounding industrialised areas within Gauteng, where most activities have a link to poor air quality. The major polluters in the area are heavy industrial activities, power stations, intensified passenger and truck traffic, household emissions, and mining activities.

Ambient air pollution refers to outdoor air contamination, which stems from natural and anthropogenic sources. Ambient air is a mixture of various gases and many other traces of gases. Ambient air pollution mainly occurs if there is a change in the geography of ambient air, the cause is either by fume, smoke, various gases or dust (WHO, 2010).

Developed and developing countries with numerous industrial facilities, cars, factories, power utilities, and household products produce compounds that emit pollutants into the air that are harmful to human and animal health and the environment. Fine matter particles have the most significant negative impact on human health (WHO, 2016). Most fine particulate matter originates from mobile sources such as vehicles and stationary sources such as power plants, industries (big industry), biomass burning, fuel combustion and households.

South Africa is home to many regions that experience significant air quality problems (Department of Environmental Affairs, 2016). Particulate matter ($PM_{10}$) and ambient sulphur dioxide ($SO_2$) concentrations are persistent pollutants in numerous parts of the country. They result from fossil fuel burning in residential, industrial and power-generating regions (Friedl et al., 2008).

The WHO (2016) identified the City of Tshwane as one of the three major air-polluted areas (with the other two being Ekurhuleni and Johannesburg) in the Gauteng Province. One of the contributing factors to such high pollution levels was the proximity of the City of Tshwane to coal mines.

This study aimed to compare two of the major pollutants in the City of Tshwane, look at the causes of these air pollutants, the impacts on human health and the environment, and identify potential solutions to help minimise air pollution caused by these pollutants in the city.

### 1.2 Problem Statement

The primary air quality problem has historically been attributed to large industries built or around clusters, where the impoverished work and stay to allow easy access to places of work or where residential properties and rentals were affordable for the poor. The construction and operation of these industries did not consider their impact on human health and the environment. These industries manufacture the most potent types of air-polluting chemicals, which are sulphur dioxide ($SO_2$) and particulate matter 10 ($PM_{10}$) (Berktas & Bircan, 2003).

Air pollution has always been an enormous challenge and a significant issue that threatens human health, damages natural and physical assets, and hinders economic growth (WHO, 2010). However, with the raised awareness of climate change and factors affecting human health and the environment, assessing and controlling air quality and significant air pollutants has become imperative. Monitoring air quality also increases the health sector's role in addressing and monitoring air pollution issues and the depletion of air quality. Air quality and increases in air pollution affect not only people's lives but also the environmental setup (Department of Environmental Affairs, 2016) and its role on future generations' wellbeing.

The National Clean Air Association (NACA) estimated that around nine million people in South Africa burn coal fuel, causing ambient air pollution (NACA, 2012). Using coal as their primary source of energy for cooking and heating has severe health implications because of the polluting emissions, which also damage the natural environment (Pan et al., 2010). Countries with large populations, such as China, have been in the spotlight for having the most polluted cities globally with physically visible forms of pollution. For example, smog and smoke, covering significant parts of the industry-dominated regions, and cities such as Beijing (China), suffer from the pollution caused by industrialisation, with reports of severe occurrences of health problems for young children and adults (Mathee & von Schirnding, 2003).

### 1.3 Aim

The main aim of this study was to establish the concentrations of two primary pollutants (sulphur dioxide ($SO_2$) and particulate matter ($PM_{10}$)) in the designated research areas, compare the two pollutants and their impact, and compare the results with national standards. This study also aimed to identify potential solutions that can assist the municipality in minimising the discharge of harmful pollutants into the atmosphere in the City of Tshwane and minimise the challenges to or negative impact on human health caused by polluted air.

**1.4 Objectives**

The specific objectives of the study were:

- To determine the concentrations of two major pollutants ($SO_2$ and $PM_{10}$) in the City of Tshwane;
- To compare the air pollutant concentrations at the three different areas of the City of Tshwane;
- To identify the possible sources of these pollutants in the City of Tshwane;
- To identify the impacts of polluted air in the City of Tshwane;
- To find and suggest solutions to minimise the effect of air pollution in the City of Tshwane.

# CHAPTER 2: REVIEW OF AIR POLLUTION IN TSHWANE (SOUTH AFRICA) AND SOURCES OF POLLUTANTS ADOPTED IN THE STUDY

## 2.1 Introduction

This study defines air pollution as any mixture of non-natural matter that changes the standard composition of ambient air. While several approaches exist to this definition, the main aim of this study was to compare the deviation of ambient air in the three study areas from the standard ambient air quality and measure the extent of existing pollution. The definition and an outline of pollutants and their various sources are listed in this study section.

Ambient air pollution is considered a global problem. It has attracted the recognition of many scientists, mainly because it results in far-reaching consequences for human health and the environment (WHO, 2016). Besides speeding up climate change and all the serious adverse effects, air pollution is also responsible for a developing range of health issues worldwide. Thus, all stakeholders must take care of the environment and protect it from decay at a global level as increased levels of air pollution lead to air-borne toxins that are dangerous to human health (Mathee & Von Schirnding, 2003).

## 2.2 Air Pollution Definition

When additional non-natural substances invade the air as gases, liquid droplets, and fine particulate solids, such as the dust of such toxins, the air becomes polluted (Vallero, 2007). Harmful air emanates from the exhausts of cars, factory and household emissions, and mining activities, among many other pollution sources, for example, veld fires and burning of forested areas. These release pollutants in the form of harmful substances to human and animal health, kill plants or hamper their growth, and damage or disturb other environmental aspects (WHO, 2010).

### 2.2.1 Air pollution mechanisms

Venter et al. (2012) outline that one of the primary mechanisms for air pollution distribution is wind. As pollutants gain access to the air, wind transports such substances. Several factors of wind distributed air pollution include, but are not limited to, a) the wind direction that determines the direction of pollutant transportation; and b) wind speed, which determines the rate of pollutant transportation. These wind parameters determine the dispersion of pollutants, the speed with which they disperse, and such distribution direction.

### 2.3 Common Air Pollutants in South Africa

The pollutants of particular concern in South Africa are particulate matter ($PM_{10}$), particulate matter $PM_{2.5}$, nitrogen dioxide, ozone, sulphur dioxide ($SO_2$), carbon monoxide, carbon dioxide, lead, benzene, mercury, dioxins, POPs, other VOC toxins controlled by global conventions confirmed by South Africa, chrome, fluoride (particulate and gas) and manganese (DEA, 2016), with the two significant pollutants being sulphur dioxide ($SO_2$) and particulate matter ($PM_{10}$).

**Table 2.1: Major sources of Air Pollution in the City of Tshwane (sourced from Tshwana.gov.za)**

| **Air pollutants** | **Anthropogenic source** |
|---|---|
| $PM_{10}$ and $PM_{2.5}$ | Domestic biomass/fuel burning<br>Industrial – fuel combustion (for example, boilers) Industrial – sand handling processes (for example, sand reclamation)<br>Vehicle exhaust emissions<br>Mining, construction and agricultural activities (for example, tailings)<br>Waste incineration and waste burning<br>Vehicle dust emissions from unpaved roads Windblown dust from exposed soil and surfaces |
| $SO_2$ | Domestic biomass or fuel-burning<br>Power generation<br>Industrial fuel-burning operations Petrochemical and chemical plants (long-range transport)<br>Transport (diesel vehicle emissions) |
| $NO_x$ and $O_3$ | Vehicle exhaust emissions<br>Domestic biomass/fuel burning<br>Industrial fuel-burning operations<br>Power generation (long-range transport) |
| $CO_2$ (not criteria air pollutant) | Power generation (primary source)<br>Industrial fuel-burning industries<br>Vehicle emissions<br>Domestic biomass<br>Fuel-burning |

## 2.4 Two Major Pollutants in Tshwane

### 2.4.1 Sulphur Dioxide ($SO_2$)

Sulphur dioxide is a primary contaminant produced by industrial processes. Small businesses that use sulphur-containing fuels as a source of energy are significant contributors to $SO_2$. Combining sulphur-containing fuels like coal and unrefined oils might be a substantial source of anthropogenic $SO_2$ emissions into the atmosphere (Venter et al., 2012; Harrison et al., 2014).

Domestic or residential biomass burning operations also produce $SO_2$ emissions (Naidoo et al., 2014). Some of these are everyday household activities where families use fuels such as wood, coal, or paraffin for heating and cooking purposes. Electricity is either scarce or very expensive to utilize regularly (Kornelius et al., 2012). In most areas within Tshwane, large informal settlements utilize such alternative fuels for cooking and heating. For example, coal is cheap, easily accessible, and poor households use it as an alternative source for cooking and heating.

### 2.4.2 Particulate Matter ($PM_{10}$ and $PM_{2.5}$)

Particulate matter exists in the atmosphere as solid or liquid particles with varied chemical compositions and sizes (Beckett et al., 1998; Kampa & Castanas, 2008; Harrison et al., 2014), and these particles are classified as primary or secondary contaminants. Primary particles are directly transferred into the atmosphere from the source, with no change in chemical composition. On the other hand, secondary particles are formed in the atmosphere by the oxidation of gases like $SO_2$ and $NO_2$ during gas-to-particle conversion and vapour condensation (Held et al., 1996; Hueglin et al., 2005; Beckett et al., 1998).

The critical anthropogenic sources of particulate matter in the environment are biomass burning (veld fires and fires used for deforestation), vehicle emissions through exhausts, material screening and crushing, industrial activity, domestic biomass burning, material handling operations, vehicle dust emissions on unpaved streets and roads, and wind erosion of exposed areas such as mine dumps and ash heaps, are the critical anthropogenic sources of particulate matter in the City of Tshwane (City of Johannesburg, 2008; Oguntoke et al., 2013).

## 2.5 Types of Air Pollutants

Pollutants are assembled into different classes, such as solid particles, liquids, and gases, and these pollutants may either be artificial or natural (WHO, 2016). Air pollution types extend from particulate matter (solid), sulphur dioxide (gas), coal combustion (solid), vehicle emissions (gas), nitrogen oxide (gas), carbon monoxide (gas), carbon dioxide (gas), ozone gas (which forms and is caused by the presence of nitrogen oxides), lead from fuel and benzene to the evaporation of petrol (Valerro, 2007).

### 2.6 Air pollution Sources

Air pollution sources can be divided into two fundamental groups, the point source (single location source) and a non-point source (multi-location source). Single location and non-point source pollution are the results of contaminants that are brought into the natural environment over a vast, widespread area (Cohen, 2016).

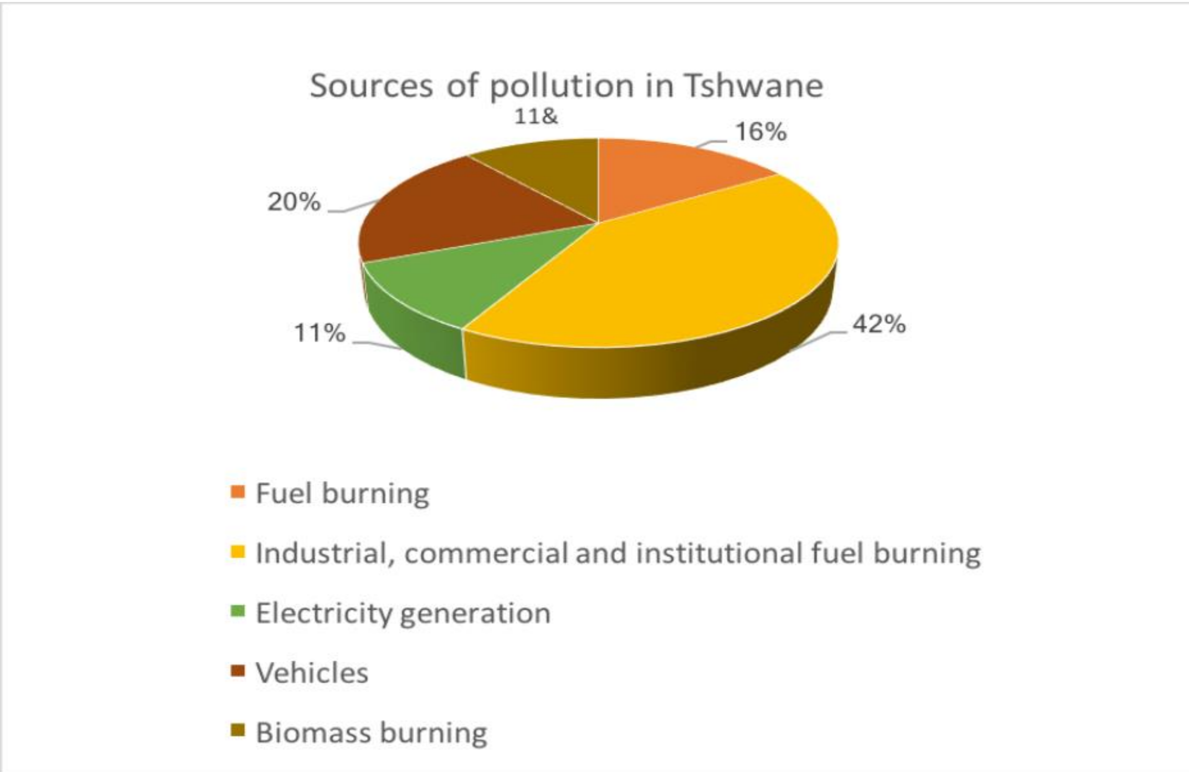



**Figure 2. 1: Figure showing the sources of pollution in Tshwane in percentage volume.**

Electricity generation, fuel burning, industrial, institutional fuel and commercial fuel burning, vehicle emissions and burning of wood and other forms of biomass are significant identified air pollution sources in Tshwane (Valsamakis, 2015). From figure 2.1, it is evident that industrial, commercial and institutional fuel-burning produces the most significant amount of chemicals (42%), which contribute a great deal to air pollution in the area

## 2.7 The Causes of Air Pollution

Globally, it was observed that the significant causes of air pollution are vehicle exhaust emissions, electricity generation, pollution from industrial plants and manufacturing plants, domestic fuel and biomass burning, veld fires, gas emissions, landfill sites, tyre burning emission, agricultural emissions, and other pollutants (Leibenberg-Enslin & Petzer, 2005). In all cases, it is evident that the contaminants are by-products and residues of activities aimed to enhance human life but contribute to the decline of the quality of human life because of the pollutants they emit.

### 2.7.1 Vehicle emissions

Vehicles (whether cars or trucks) are essential machines for the supply chain, transportation sector, and human transport. Still, their exhausts emit polluted air that adds to the depletion of air quality, especially in urban areas, where the population of automobiles is pronounced. Part of the contaminations regarding vehicle exhaust emissions incorporate gases (CO, PM, $CO_2$, $CH_4$, $NO_2$, $C_6H_6$, $O_3$, aldehydes and polycyclic fragrant hydrocarbons (PAHs) and lead (Pb)) (RSA, 2009) that emanate as both a complete and incomplete combustion of fuel.

South Africa has observed a dramatic growth in vehicles on the roads (Figure 2.2). The change in the number of cars has also brought about an increase in fuel utilisation (WHO, 2016). It is evident that with such an increase, vehicle combustion engine-based air contamination is worsening in line with the expanding vehicle production.


**Figure 2. 2: South African new car sales in 2017. (Sourced form NAAMSA South Africa http://www.tradingeconomics.com)**

### 2.7.2 Industrial emissions

A great deal of energy is required in industry to drive the machines used to produce value-added products. Conventionally, petroleum fuels consumed to power such machinery emit pollutant substances associated with the source of the crude oil, greenhouse $CO_2$ and CO, among other gases. Some industries, for example, mining and manufacturing, emit solid particles into the atmosphere as dust, caused by the crushing of raw material and the movement of machines. South Africa is no anomaly for air contamination issues caused by industrialisation and is in line with other developing countries. Therefore, the immediate impact of air contamination is especially pronounced in and around industrial areas. Thus, it is essential that technology improvements have to be made and implemented to reduce the dust that emanates, for example, from the City of Tshwane's industrial zone (CoTMM, 2014). The use of scrubbers, dust captures and wet combinations are examples of potential dust reduction practices.

The adverse effects of air contamination are generally experienced alongside such operations. Sometimes, the negative impacts − whether anticipated or unanticipated − can be experienced even after these operations have stopped and still affect humans, animals, and the environment, the victims of pollution, even long after the cause of the decay has been removed. These effects are noticeable in the Witwatersrand, Gauteng, where previously mined areas still experienced the after-effects in these regions, where escalated mining exercises turned into rising problems decades later (Wernecke et al., 2015).

### 2.7.3 Electricity generation and consumption

In South Africa, the production of electricity or power is still heavily reliant on conventional fossil fuels, such as coal, which accounts for about 81% of the country's coal use for power generation, with the state-owned utility Eskom providing around 95% of the country's overall electricity (Levy et al., 2002). Pollutants such as particulate matter, sulphur dioxide, nitrogen oxides and mercury are a product of the use of coal-fired power plants (Levy et al., 2002).

Electricity generation through coal power plants contributes to a significant amount of air pollution and thus, causes adverse environmental and health effects. When coal is burnt to generate electricity, combustion occurs and releases a combination of chemicals into the environment and, therefore, the human body (WHO, 2016).

### 2.7.4 Domestic fuel burning

In a global context, the rising levels of contamination from pollution caused by coal-burning is mirrored in South Africa, where the demand is for alternative energy creation and sustainability of resources that do not cause decay. Residential fuel sources such as coal, wood, and paraffin are used for cooking and heating in South African lower-class houses and informal settlements. (Koppman et al., 2011), and caused by a lack of alternative or cheaper sources. The Tshwane area has one of the largest informal settlements in Gauteng, which has resulted in a significantly higher percentage of pollution caused by domestic fuel burning (DEA, 2010).

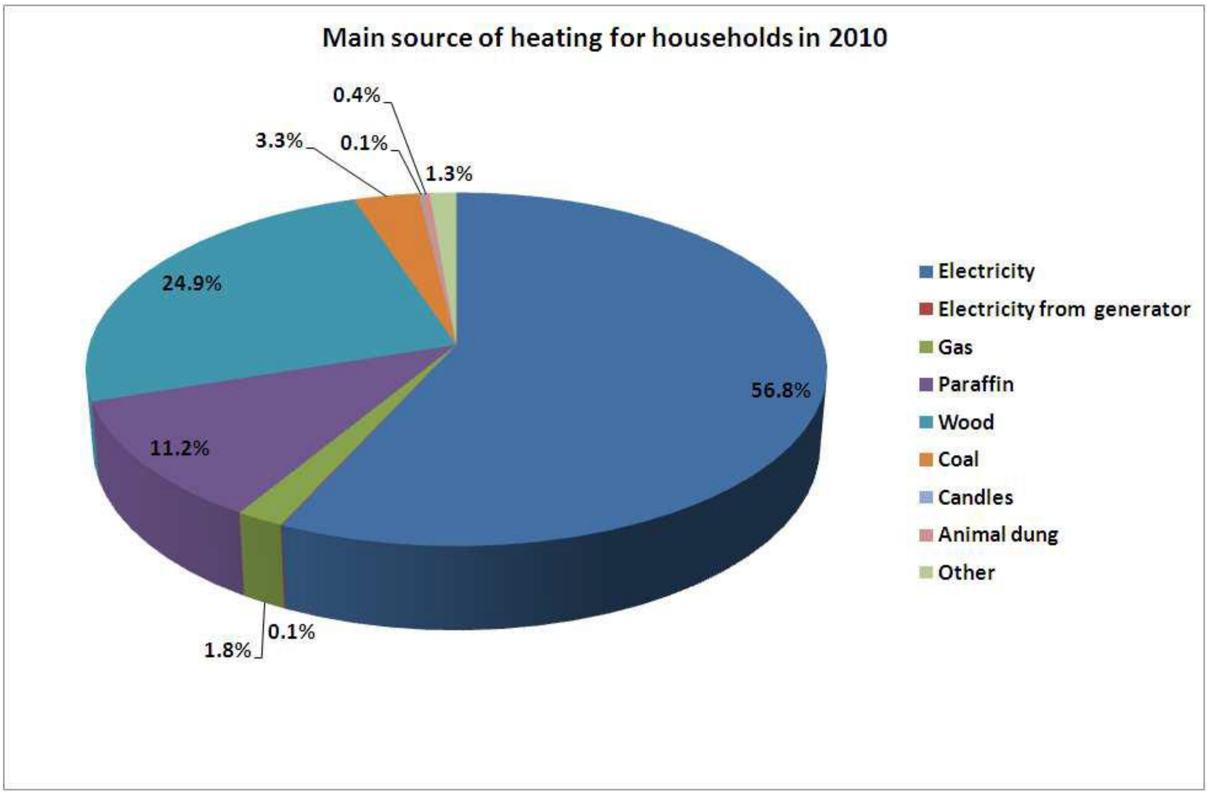



**Figure 2. 3: Pie chart showing the primary heating source for households in Tshwane in 2010 in their percentage volume (Source: DEA 2010).**

Many of the poorer households in Tshwane use simple, small-scale appliances such as household cooking stoves. Many of these stoves do not have vents (stoves that do not have pipes or hoods to exit toxins from the living condition) (Koppman et al., 2011).

Informal settlements mainly utilise paraffin, coal, gas, wood, candles, and animal dung as heat sources (Figure 2.2). These are the primary pollutant producers stemming from households, and they add a great deal to ambient air pollution (Friedl et al., 2009).

### 2.7.5 Biomass burning

Biomass burning is a significant source of particulate outflows into the air. Poisons related to burnt biomass add to nursery gases ($CO_2$, $NH_4$ and NO), CO, and VOCs, particularly in tropical and subtropical climates (WHO, 2016). By interacting with hydroxyl radicals, CO, $CH_4$, and VOC release influence oxidation to constrain the environment. The spread of NO and VOCs prompts the development of $O_3$ and other oxidants. Nearly 90% of all biomass discharges that are burnt are believed to be anthropogenic (Koppman et al., 2011). Fires made by humans are utilised for various purposes, including agricultural development, shrubbery control, and weed control.

### 2.7.6 Veld fires

Veld fires are a severe challenge in South Africa, as they represent a potential hazard to life. Landfills, the type of fuels used to start the fires, coherence, structure, dampness, and the weather and wind levels at the time of the fires are the components that significantly impact fire action (Forsyth et al., 2010).

As indicated by an investigation by the Board of Logical and Mechanical Exploration (Forsyth et al., 2010), there was a stamped drift in flame frequency from the affected eastern to western regions and from north to a lesser degree to south. The Succulent Karoo and Nama Karoo, which had almost no fires, are found in the north-western part of the site, where the primary biomes are found. The areas with the highest fire frequency were in mountainous areas (Forsyth et al., 2010).

### 2.7.7 Landfill site gas emissions

Landfill sites are true hotspots for released gases like $CH_4$ and $CO_2$, concerning since they are nursery gases and pose a threat to environmental change (Cohen & Winkler, 2014). Landfills emit various odorous and toxic gases, such as hydrogen sulphide and volatile organic compounds (VOCs). Cancer-causing chemicals such as benzene and methylene chloride are also released from landfills (Abushammala et al., 2009).

The pollutants emitted from landfills result from the disintegration and breakdown of the waste material. They are brought by a wide range of toxic and chemical waste, combustible waste and other matter within the landfill. Landfill gas emissions are of concern because of their potentially harmful effects on human wellbeing, especially any cancer-causing agents and harmful poisons, for example, chlorobenzene (Mathee & von Schirning, 2003).

### 2.7.8 Tyre burning emissions

Controlled and uncontrolled burning of tyres leads to polluting discharges or emissions. Uncontrolled burning of tyres refers to open tyre fires, resulting in highly toxic fumes and smoke, emissions that combine criteria poisons, such as $PM_{10}$, $PM_{2.5}$, CO, $SO_2$, and $NO_2$

discharge them into the air. Discharges from controlled sources are much lower, and as a general rule, these sources have proper air contamination control speed for control of particulate outflows (Mathee & von Schirning, 2003).

Tyre burning emissions have shown spikes in particulate matter $PM_{10}$ in the environment. These pollution levels in the air greatly exceed the Environmental Protection Agency (EPA) maximum allowance limits standards for $PM_{10}$ concentrations.

### 2.7.9 Agricultural emissions

Agriculture is a vital sector in South Africa and contributes significantly to food security in the country. However, farming exercises are also associated with particulates and gases, which combine particulate emissions created by mechanical activities, vaporous and particulate discharges caused by compost and synthetic or chemical treatments, and vaporous and particulate emanations caused by agricultural land practices (Ritter, 2005).

Globally, the primary concerns are around the gaseous discharges created by animal farming, especially dairy and meat farming, the decomposed animal by-products, and the chemicals used to clean animals, such as sheep, pigs, etc. goats and chickens. Some of the evaluated discharges incorporate smelling salts (an ozone-depleting substance) and hydrogen sulphide (Shindell et al., 1998).

## 2.8 The Effects of Ambient Air Pollution on Human Health and the Environment

Poor air quality has a very harmful effect on human health, animal health, and the environment. The harmful effects on human health have been recorded to lead, for example, to chronic bronchitis, asthma, and advancing the intensity of attacks (WHO, 2010). Other physical symptoms of the harmful effects of poor air quality include chest pains, dizziness, digestive issues, watery eyes, and a fever (Cohen, 2016), among many other illnesses and health problems. In recent years, several European studies have associated air pollution in cities with various impacts on human health, including respiratory diseases in children and mortality implications in adults (Pan et al., 2010). Many of these investigations employed $NO_2$ contrasts as the primary exposure variable, raising the question of whether such relationships are entirely found for $NO_2$ or if $NO_2$ serves as a proxy for a complex combination of pollutants emanating from vehicular traffic, industrial, and home activities (Mauderly et al., 2010).

Studies worldwide have also focused on environmental air pollution and air quality because poor air quality affects the wider environment, contributes dramatically to climate change and the production and maturity of forests, and is the direct source of the decrease in the number of crops produced.

Some pollutants are directly responsible for destroying the ozone layer. As the ozone layer is depleting, harmful radiation can easily reach the Earth's surface. The radiation, in turn, can decrease plant development and affect aquatic life (Gent et al., 2003). Reduced production of essential or staple crops such as rice, corn/maize, wheat and sunflowers can also be negatively affected by human activities that contribute to the increase of greenhouse gases in the atmosphere. The development of these gases acts similar to a blanket that traps heat close to the Earth's surface, increasing the temperature of the oceans and the land surface, and thus warming the Earth (Shindell et al., 1998).

In the past, the leading causes of air pollution were easily identifiable, ranging from corrosion caused by industries, and it was easy to identify which industries contributed most towards air pollution (Leibenberg-Enslin & Petzer, 2005). Today, firm air pollution laws, excellent environmental awareness plans, programmes, environmental protection strategies, campaigns created by local communities, national governments and international ecological governing bodies make it more difficult for factories to pollute in post-industrial countries like Britain and the United States.

According to the WHO's (2010) air pollution database, South Africa was ranked 30th for poor air quality. About 20 000 people die every year due to harmful air pollution in the country, with the illnesses costing the economy nearly R300 million (Krzyzanowski & Cohen, 2010). Polluted air affects older adults, who are not strong or resilient enough to combat the effect of harmful air pollutants, and the poor because they work and live in highly polluted areas and cannot protect themselves against the harmful pollutants or avoid the risk of exposure. As a result, this portion of the population is at a double disadvantage. They become too sick to work and cannot incur the resultant medical costs (Department of Environmental Affairs, 2016).

## 2.9 Air Quality Legislation

The legislation put in place to ensure quality air focuses on the worldwide impact of international and local projects that will release pollutants into the environmental sphere

(WHO, 2010), how the contaminants are removed and how they aim to minimise or mitigate any impact on the environment that the release of these pollutants might cause. The international and local control bodies have set legal limits for particulate matter and sulphur dioxide, monitoring emissions. In theory, no construction of power utilities if they increase the ambient chemical levels such as sulphur dioxide over the acceptable levels. Therefore, according to the set air quality standards and allowed emissions, all new industrial activities must comply with the latest environmental laws. Many large-scale industrial are polluters and have a time frame to repair their manufacturing plants to become fully compliant (Wright et al., 2011).

Previously, the Air Pollution Prevention Act (No. 45 of 1965) (APPA) regulated air pollution in South Africa to prevent atmospheric disintegration. The APPA was in charge of managing and regulating dangerous gas emissions, mainly from industrial sources. It allowed for the formation of a National Air Pollution Advisory Committee as well as other related topics. However, there are numerous obstacles to overcome facing the APPA at the time, and it did not consider descriptive emissions or the combined effects of many emission sources on ambient air quality. Furthermore, the APPA was unable to adopt adequate air quality standards due to the lack of a legal framework to apply such measures (Held et al., 1996). As a result, the APPA was deemed obsolete (South Africa, 2003).

Following the APPA, the National Environmental Management: Air Quality Act No. 39 of 2004 (NEMAQA), this act was implemented to monitor and manage South African air pollution. The National Ambient Air Quality Standards (NAAQS) were developed mainly for South Africa due to the adoption of NEMAQA. Different industrial polluters had their own source-specific air pollution control strategies designed, allowing for more effective air quality regulation and management in South Africa (DEA, 2013). The Department of Environmental Affairs and various municipalities have been tasked with establishing and implementing air quality management policies and developing and implementing local emission and ambient concentration guidelines and regulations. These obligations are essential for South Africa's efficient air quality management (DEA, 2009).

However, human, financial and technological resources are limited in South Africa regarding air quality measures. A precedence approach needed to be employed to focus on the available resources in areas with inferior air quality. In keeping with the requirements set by the

NEMAQA, there are developments of an Air Quality Management Plan (AQMP) in the City of Tshwane (Tshwane Municipality) (2014). The main objectives of the plan are:

a) To achieve acceptable air quality standards;
b) To reduce harmful impacts of air pollution on the environment and human health;
c) To provide a clean environment for citizens;
d) To support and promote climate change protection programmes.

The NEMAQA has created ambient air quality standards for eight benchmark pollutants, including $SO_2$, $NO_2$, $PM_{10}$ and $PM_{2.5}$, $O_3$, CO, and lead, with great success (Table 2.2). When certain compounds are present in the atmosphere over a specific level, they are harmful to human health. The ambient air quality standard establishes a reasonable maximum concentration at which air pollutants can persist in the environment without threatening human health (WHO, 2010).

**Table 2.2: Outdoor air quality standards for eight benchmark pollutants (WHO, 2018).**

| Pollutants | Average period | Concentrations ($\mu g/m^3$) | Concentrations | Frequency of exceedance |
|---|---|---|---|---|
| Sulphur dioxide ($SO_2$) | 10 minutes<br>1 hour<br>24 hours<br>1 year | 500<br>350<br>125<br>50 | 191<br>134<br>48<br>19 | 526<br>88<br>4<br>0 |
| Nitrogen dioxide ($NO_2$) | 1 hour<br>1 year | 200<br>40 | 106<br>21 | 88<br>0 |
| Particulate Matter ($PM_{10}$) | 24 hours<br>1 year | 120<br>75<br>50<br>40 | -<br>- | 4<br>0 |
| Particulate Matter ($PM_{2.5}$) | 24-hour average<br>Annual average | 65(2)<br>40(3)<br>25(4)<br>25(4)<br>20(3) | -<br>- | 0<br>0 |

| | | | | |
|---|---|---|---|---|
| | | 15(4) | | |
| Ozone ($O_3$) | 8 hours | 120 | 61 | 11 |
| Carbon monoxide (CO) | 1 hour<br><br>8 hours (calculated on one hourly average) | 30 000<br><br>10 000 | 26000<br><br>8 700 | 11<br><br>88 |
| Lead (Pb) | 1 year | 0.5 | - | 0 |

Ambient air quality monitoring is a critical part of the AQMP's role. It takes into account a continuous assessment of ambient air pollution levels in comparison to the South African National Ambient Air Quality Standards. The City of Tshwane's air quality monitoring system aids in achieving the AQMP's objectives by allowing the administration to recognize global and geographical patterns in air pollution affecting the area, which is fundamental for powerful air quality administration (South Africa, 2009).

The transition from the APPA to the new AQA addressed the need to shift away from previously used, mainly source-based air pollution control strategies in favour of integrated impacts-based air quality management. The national system for air quality administration is one of the most critical air quality administration devices in South Africa, as mandated by the AQA. The system has a substantial role in filling in a plan for air quality administration and is expected to accomplish the air quality requirements and standards stipulated in the AQA. Since launching the AQA, different approaches have been used to enhance the air quality and ensure that humans and the environment are considered at all times. The identification of highly impacted territories and setting new targets for air quality indexes, the AQMPs, as expressed in the AQA, and as a considerable aspect of the ecological administration cycle, have been a portion of the strategic goals and measurements set as a part of achieving the standards necessary to securing human wellbeing and the South African environment. Reactions to vehicle exhaust emissions or discharges and household emissions caused by burning fuels are incorporated in the national outflows technique and the system for tending to air contamination in low-income homes (WHO, 2006).

Valsamakis (2015) examined the ambient air quality standards of the City of Tshwane, which fall under the provincial air quality standards of the Gauteng province. The primary focus of the research was to examine substances in the Tshwane region, such as nitrogen dioxide, sulphur dioxide, particulate matter, ozone, carbon monoxide lead and benzene (Tshwane Municipality, 2014).

**Table 2.3: The proposed provincial ambient air quality standards for the City of Tshwane**

| Substances | 10 Minute maximum (µg/m³) | 1-hour maximum (µg/m³) | 8-hour maximum (µg/m³) | 24-hour maximum (µg/m³) | Annual average (µg/m³) |
|---|---|---|---|---|---|
| Sulphur Dioxide ($SO_2$) | 500 | 350 | - | 125 | 50 |
| Nitrogen dioxide ($NO_2$) | - | 200 | - | - | 40 |
| Carbon monoxide (CO) | - | 30 000 | 10 000 | - | - |
| Particulate matter ($PM_{10}$) | - | - | - | 75 | 40 |
| Ozone ($O_3$) | - | 200 | 120 | - | |
| Lead (Pb) | - | - | - | - | 10 |
| Benzene ($C_6H_6$) | - | - | - | - | 5 |

Of all the annual ambient air pollutants for the City of Tshwane, $SO_2$ has the highest average of 50(µg/m³); $NO_2$ and $PM_{10}$ have the second-highest average of 40(µg/m³); followed by lead with an average of 10(µg/m³) and benzene with an average of 5(µg/m³). Sulphur dioxide has for a long time been the most common air pollutant in the area, followed by nitrogen dioxide and $PM_{10}$. Road traffic exhaust fumes and fossil fuel combustion create these pollutants (SAAQIS, 2016).

Regarding $SO_2$ contamination within the City of Tshwane, Pretoria Central is the most polluted area in the City of Tshwane, and Mamelodi East is the most contaminated with $PM_{10}$; this is caused primarily by the proximity of the industrial regions and their emissions in these regions (City of Tshwane Metropolitan Municipality, 2014).

Wright et al. (2011) examined ambient air pollution and described it as a severe challenge to the City of Tshwane. According to the study, the north-western and the north-eastern zones had received the lowest number of complaints from residents over the past five years regarding the poor air quality, while the eastern and central zones of the City of Tshwane had the highest number of complaints. The number of complaints from the various zones grouped by region illustrates which areas in Tshwane were the most polluted and had the most reports and complaints.

## 2.10 Developing Air Quality Issues in South Africa

According to the National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004), South Africa faces different air contamination challenges, which incorporate industrial activity issues, for example, modern emissions and fuel consumption (DEA, 2016). However, there are many other air quality challenges the South African population is facing. These developing issues include tyre burning emissions, waste outflows, pollution from filling stations, miniature boilers, black-top plants, and rising need poisons, such as mercury, dioxins and furans, formaldehyde and poly sweet-smelling hydrocarbons.

## 2.11 Ambient Air Quality Monitoring in South Africa

One of the most critical aspects of the air quality techniques and administration for deciding to encompass air quality is the analysis of air quality-related information (DEAT, 2006b). Air quality monitoring addresses an integral part in the overall goal to improve air quality by providing the fundamental and sound reasons for arrangement and system improvement, consistency measures against the set targets, and the implementation of the relevant action. A wide variety informs a considerable measure of air quality monitoring of observing organisations in South Africa; these organisations use a scope of watching strategies and methodologies. The National Surrounding Air Quality Checking System (NAAQMN) employs approximately 94 of the government's air quality observing stations. It operates by every one of the three circles of government (SAAQIS, 2016), national, provincial and local.

# CHAPTER 3: DATA, SITE DESCRIPTION AND METHODOLOGY

The current study used ambient $SO_2$ and $PM_{10}$ data from SAWS from January 2009 to December 2018 and data collected at Tshwane's three designated areas: Rosslyn, Pretoria West and Mamelodi. The study aimed to investigate how $SO_2$ and $PM_{10}$ vary in these regions and assess the possible effects of these pollutants on the environment.

The study focused on the pollutants' modes of transportation, identifying what caused an increase in air pollution levels and how these concentrations could be decreased, minimised or even eliminated. The study also aimed to arrive at viable solutions to the current air pollution problem. It also suggested achieving recommendations based on analysis of the seasonal variations of $SO_2$ and $PM_{10}$ concentrations from ground-based data over the three monitoring stations. In this study, and to address the possible causes in the areas of study, the meteorological data collection for the three sites were compared with standards of good quality air that South Africa follows. The evaluation of the extent of pollution was based on the background outlined below.

## 3.1 Site Description and Information

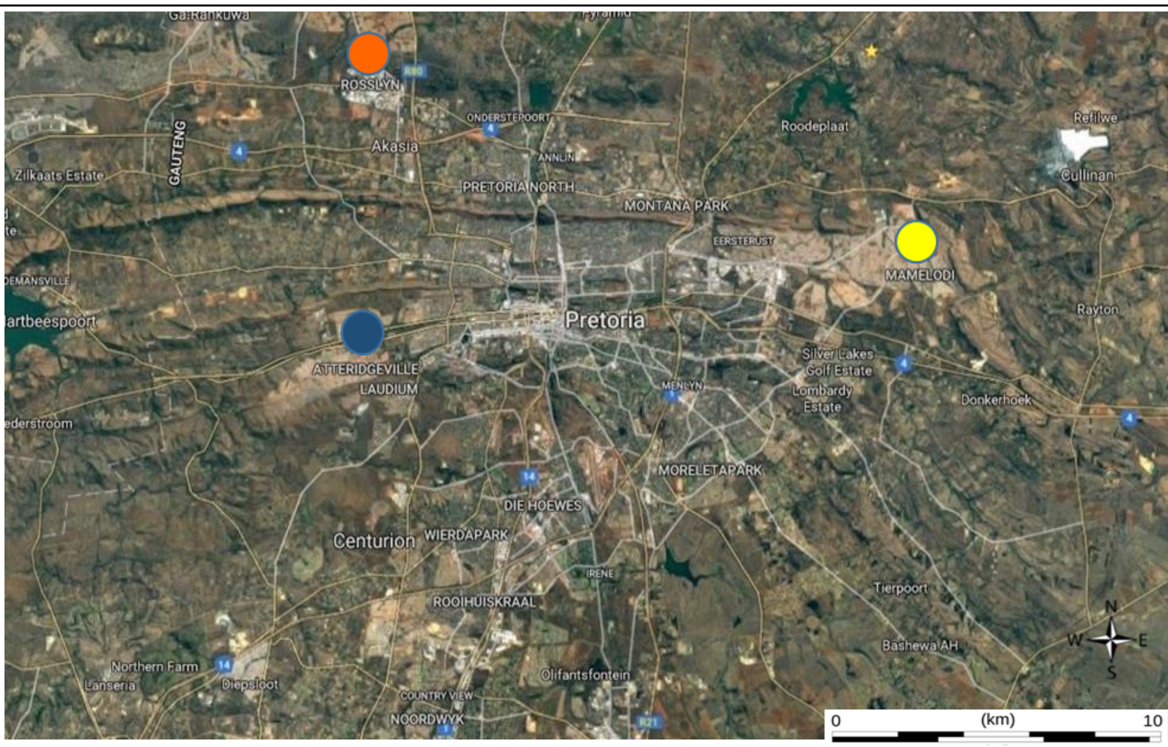



**Figure 3.1: Map representing the study area with the sampling points (Sourced from https://www.google.co.za/maps.co.za)**

Figure 3.1 above shows the sampling sites on the Google image. The sampling sites are identified on the map as sampling site 1, Rosslyn (orange); sampling site 2, Pretoria West (blue); and sampling site 3, Mamelodi East (yellow).


**Figure 3.2: Map of the City of Tshwane (Sourced from http://www.tshwane.gov.za).**

The coordinates of the chosen sampling sites were listed using the geographic coordinate system as follows: Rosslyn (25.6233° S, 28.0859° E), Pretoria West (25.7503° S, 28.1550° E) and Mamelodi East (25.7102° S, 28.4008° E).

### 3.1.1 Site background

The Magaliesberg Mountains, as well as many smaller ranges, cut through the city of Tshwane, potentially affecting air pollution dispersing and influencing the location of monitoring stations under certain conditions. $SO_2$ and $PM_{10}$ were the two pollutants tested over a wide range of parameters by the National Department of Environmental Affairs (RSA, 2009).

$SO_2$ and $PM_{10}$ were the two pollutants measured across all permanent monitoring sites, hence using these pollution concentrations in this study.

The dominant factors that influence the climate in a location are latitude, elevation and the distance from the ocean. Latitude relates to the amount of radiation received, with lower margins receiving more radiation than higher latitudes. Temperature decreases with increasing height; hence, the climate-related to elevation has to be considered. The ocean has a moderating effect on the temperature range, and coastal areas are generally more relaxed and wetter than inland areas. Other factors that influence climatic conditions are topography and local winds.

Background meteorological conditions are essential when assessing the impact of pollution sources on the surrounding areas, as they instruct the transport, dilution and dispersion of pollutants in ambient air. Wind patterns, rain, pressure, clouds, humidity and temperature, can affect how fast or how slow pollutants move away from a specific area and in which direction they will move.

### 3.1.2. Possible sources of $SO_2$ and $PM_{10}$ pollution in the City of Tshwane

$SO_2$ is emitted by burning fossil fuels such as coal, oil, diesel, and other materials containing sulphur. Sources of sulphur emission include, among others, power plants, metal processing and smelting facilities, and vehicles. Coal-burning in industrial factories or power plants and biomass burning in low-income residential areas and informal settlements contribute to the production of $SO_2$. The emission records have shown that coal-fired power plants and vehicle emissions are significant contributors to air pollution.

**Figure 3.3: Coal-fired power station Eskom (sourced from https://www.eskom.co.za).**

High levels of $NO_x$ may elevate the concentrations of $PM_{10}$, as cited by Vardoulakis and Kassomenos (2008). Traffic is a significant source of high $PM_{10}$ levels in Africa, similar to many other regions across the globe, but the two primary sources of $PM_{10}$ in the City of Tshwane are domestic fuel burning and natural sources. In other areas of the world, industrial emissions and the ambiguous 'unspecified source of human origin' factors contribute more to polluting emissions. $PM_{10}$ and $PM_{2.5}$ are essential indicators of air quality and health risks (Wichmann, 2016).

**Figure 3.4: Star Gas station in Pretoria (sourced from https://stargas.co.za)**

According to Alvarez & Paranho (2012), studies suggest that emissions from the oil and gas industry could be comparable to emissions from other large sources in some concentrated locations. Furthermore, while coal-fired power plants emit significantly more greenhouse gases (GHGs) than natural gas (NG)-fired power plants, concerns have been raised about how upstream emissions associated with the extraction, processing, and transportation of each fuel affect the relative climate footprint of NG when the entire fuel cycle is considered.

Natural gas leaks and normal venting during extraction, processing, and transportation result in emissions of GHGs and, depending on the local composition of unprocessed gas, other pollutants, which contribute to locally and regionally high air pollution that may pose risk to human health.

### 3.1.3 Ambient pollutant monitoring

To monitor the pollutants in the ambient air, the City of Tshwane Metropolitan Municipality (CoTMM) established seven permanent air monitoring stations and one mobile station within its municipal boundaries. All the permanent monitoring stations within the area are fully functional. More than 80% of the data is recovered at most of the stations. The data is captured, stored, validated, analysed, and reported to SAAQIS daily. The air-monitoring stations and one mobile station are situated in Bodibeng (Region 1), Rosslyn (Region 1), Booysens (Region 3), Pretoria West (Region 3), Tshwane Mobile (Region 3), Olievenhoutbosch (Region 4), Mamelodi (Region 6), and Ekandustria (Region 7). This study obtained secondary data at three of the eight air monitoring stations (Pretoria West, Rosslyn, and Mamelodi).

### 3.1.4 Air pollution standards

**Air pollution standards for $SO_2$**

This study follows the guidelines set by the national standards for air pollution determined by the concentrations of a given pollutant over a given period (WHO, 2016). Within this framework, concentrations are considered acceptable considering what is known about the effects of every pollutant on the environment and human health (SAWS, 2009). They can also be used as a benchmark to check if pollution levels in another area improve or worsen. Exceedance of a standard is a period defined in each measure, where the concentration is higher than that set by the bar. The criteria could also be expressed in terms of different averaging times to compare the difference between pollutants. The total number of days on which an exceedance has been recorded is often reported (Josipovic, 2009). A summarised version of the air quality standard guidelines for $SO_2$ is listed in Table 3.1 and Table 3.2. The reference method for the analysis of sulphur dioxide is ISO 6767:1990 (reviewed in 2012).

**Table 3.1: National ambient air quality standards for $SO_2$ (2009)**

| Average period | Concentration | Frequency of Exceedance | Compliance date |
|---|---|---|---|
| 10 minutes | 500 (191ppb) | 526 | Immediate |
| 1 hour | 350 (134ppb) | 88 | Immediate |
| 24 hours | 125 (48ppb) | 4 | Immediate |
| 1 year | 50 (19ppb) | 0 | Immediate |

**Table 3.2: Ambient air quality guidelines and standards for $SO_2$ for various countries and organisations (Government Gazette, 2009).**

| Authority | Maximum 10- minute average (µg/m³) | Maximum 1- hour average (µg/m³) | Maximum 24- hour average (µg/m³) | Annual average concentration (µg/m³) |
|---|---|---|---|---|
| South African standards (AQA) | 500 | - | 125 | 50 |
| SANS limits (SANS 1929:2005) 500b – 125b 50 | 500 | - | 125 | 50 |
| Proposed South African standards (Government Gazette No. 28899, 9 June 2006) | 500 | 350 | 125 | 50 |
| Australia | - | 524 | 209 | 52 |
| European Countries | - | 350 | 125 | 20 |
| World Bank (General Environmental Guidelines) | - | - | 125 | 50 |

| | | | | |
|---|---|---|---|---|
| World Bank (Thermal Power Guidelines) | - | - | 150 | 80 |
| United Kingdom | 266 | 350 | 125 | 20 |
| United States Environmental Protection Agency | - | - | 365 | 80 |
| WHO (2000) | 500 | - | 125 | 50<br>10-30 |
| WHO (2005) | 500 | - | 20p | - |

Table 3.2 gives the ambient air quality guidelines and standards for $SO_2$ for various countries and organisations. Since each country follows its standards and procedures, which it needs to abide by to avoid any exceedances, different criteria must be compared to establish the overlap within the known global standards.

### Air pollution standards for $PM_{10}$

Days with one or more exceedance of the hourly average threshold given for "high" gaseous pollution concentrations or the average daily entry for "high" PM10 concentrations are classified as high-pollution days.

**Table 3.3: High pollutant days**

| Average period | Concentration | Frequency of Exceedance | Compliance date |
|---|---|---|---|
| 24 hours | 120 | 4 | Immediate-31 December 2014 |
| 24 hours | 75 | 4 | 1 January 2015 |
| 1 year | 50 | 0 | Immediate-31 December 2014 |
| 1 year | 40 | 0 | 1 January 2015 |

**Table 3.4: Air quality standards for inhalable particulates ($PM_{10}$) for various countries and organisations (WHO, 2018).**

| **Authority** | **Maximum 24-hour concentration (µg/m³)** | **Average annual concentration (µg/m³)** |
|---|---|---|
| South African standards (AQA)* | 180 | 60 |
| SANS limits (SANS 1929:2 005) | 75<br><br>50 | 40<br><br>30 |
| Australia | 50 | - |
| European Countries | 50 | 30<br><br>20 |
| World Bank (General Environmental Guidelines) | 70 | 50 |
| World Bank (Thermal Power Guidelines) | 150 | 50 |
| United Kingdom | 50 | 40 |
| United States Environmental Protection Agency | 150 | 50 |
| WHO | 50 | 20 |

Table **3.4** above shows the air quality standard for inhalable particulates ($PM_{10}$) according to different authorities over 24 hours and an annual average.

### 3.2 Methodology

Specific to this study, data for $SO_2$ and $PM_{10}$ was collected from the City of Tshwane (through SAAQIS). The data originators employed a Fluorescence $SO_2$ Analyser (Model 100E; S/N: 2891) to measure ambient $SO_2$ concentrations and a $PM_{10}$ analyser to measure $PM_{10}$.

Sulphur dioxide was measured continuously by the principle and guideline of absorbed ultraviolet (UV) light. The samples were drawn through the sample bulkhead through a hydrocarbon "kicker", which removes hydrocarbons from the samples by forcing the hydrocarbon molecules to penetrate through the tube wall. The pieces flow into the fluorescence chamber, where pulsating UV light excites the $SO_2$ molecules. As the excited $SO_2$

molecules deteriorate to lower energy states, they emit UV light proportional to the $SO_2$ concentration (SAWS, 2009).

Ambient air pollution concentrations were analysed daily and monthly by region and type of pollutant. The reason for conducting the study over differing months of the year was to study the seasonal effects that might be present and might influence people's health caused by exposure variables under investigation. Ambient quality monitoring stations and satellite data were used to analyze ambient $SO_2$, while geographic information systems (GIS) were used to identify national ambient air quality requirements exceedances.

Wind directions reported at air quality monitoring stations were provided to provide insight into the usefulness of utilizing nearby AQ monitoring stations as a proxy for ambient air quality and to examine how pollutant transportation direction affects the environment. As a result of the instrument and power failure, missing data was discovered. These occurrences were identified as such, and the resulting data was cleaned before being analyzed.

Particulate matter ($PM_{10}$) was measured continuously by laser light scattering. The samples were drawn through the bulkhead into the instrument measurement cell. The gas stream passed down through a laser beam, which was diverted by the particles. The angle of reflection or refraction was utilised to calculate the particle size.

$SO_2$ was obtained from the South African Weather Services. The information was saved in a Microsoft Excel Spreadsheet containing a distinguishing identification number, date, time, temperature, mugginess and individual weightings of filters for each weighting session. The data was labelled by the sampler, where it had to be sent to GFC Global (2019).

### 3.3 Data Collection

**Ground-Based Data**

First, the types of data sources that the researcher worked with have to be understood better to explain the limits and scope of this work. Ground-based data in this work is referred to as information gathered in the field. For example, during a review of land resources, data collected on the ground, and information derived from there to interpret remotely sensed data (GCOS, 2003). Furthermore, ground-based data might ordinarily relate to weather, soils, and vegetation types and conditions. For example, ground-based data indicates the steady warming of the atmospheric environment (World Meteorological Organization, 2016).

It should be noted that the data for this study was obtained only at the three continuous air quality monitoring stations. These monitoring stations constantly test and sample ambient air and provide instant readings to the nearest monitoring centres. This enhances the reliability of the presented information.

Secondary data was obtained from sampling campaigns done by the South African Weather Service (SAWS) per month from 1 January 2009 until 30 December 2018 (with additional available data from previous months). Ambient $SO_2$ and $PM_{10}$ concentrations were monitored at the permanent ambient air quality monitoring stations in Mamelodi, Rosslyn and Pretoria West, where the central air polluting activities occur.

The SAWS data was obtained at the continuous air quality monitoring stations in Tshwane. The CoTMM in Gauteng Province has seven permanent air monitoring stations and one mobile station. For this study, the researcher focused on three stations in Mamelodi (25.7102° S, 28.4008° E), Rosslyn (25.6233° S, 28.0859° E) and Pretoria West (25.7503° S, 28.1550° E).

**Figure 3.5: Air-monitoring station in the City of Tshwane**

Each of the three stations is fully equipped to observe and measure the following parameters at a temporal resolution of 1 minute: Sulphur dioxide ($SO_2$), particulate matter of aerodynamic diameter >10 µm ($PM_{10}$), particulate matter of aerodynamic diameter > 2.5µm (PM2.5), oxides of nitrogen ($NOx = NO + NO_2$), ozone ($O_3$), carbon monoxide (CO), VOCs (benzene, toluene, ethyl benzene, xylene), solar radiation, pressure, wind speed, wind direction, relative humidity and rainfall and temperature.

**Figure 3.6: Inside the air-monitoring station**

The high volume air sampler, which includes the filter holding assembly, high capacity blower, U-tube manometer, rota meter, impinges housed in a detachable fibre case, inlet filters, voltage stabiliser, and a timer, was used at the monitoring sites, as well as the particulate matter calculator, which was used to calculate suspended particulate matter from the high volume sampler method: [CP_calculated_fields id ="6″].

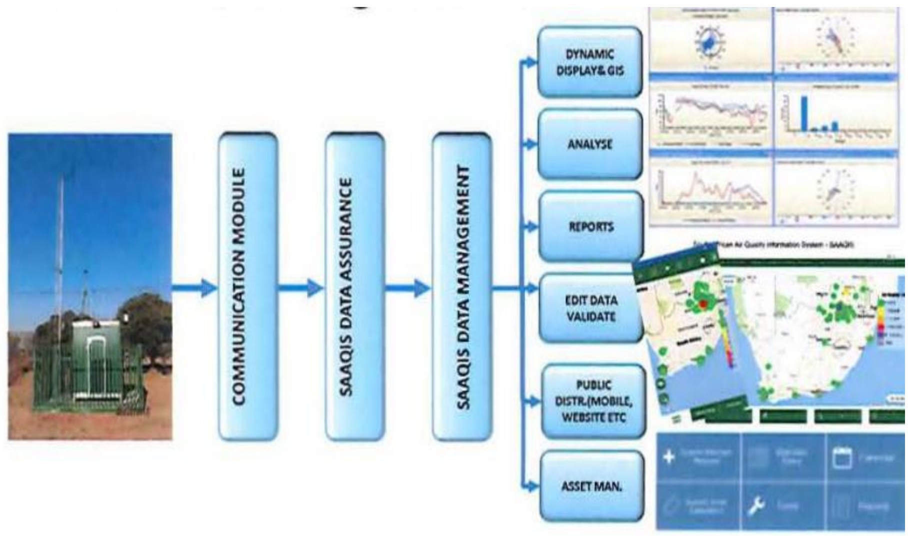



**Figure 3.7: Ambient monitoring flow data**

Similar to the methodology applied by Bond (2007), the sampling and testing functions of the air pollutants in the Mamelodi East, Rosslyn situated north of Pretoria Central, and the Pretoria CBD areas were placed into four components. These components included sampling sites' selection and location, air quality parameters, sampling frequency, and collection and analysis methods.

The ambient air quality data used in this research was obtained from SAWS and analysed through Openair, an R-Studio software. The software runs with the Interactive Data Language (IDL) and uses various algorithms for data processing (Carn, 2011). Openair is an R package for air quality data analysis. It is primarily developed for the analysis of air pollution measurement data and is generally used in the atmospheric sciences. It consists of many tools for importing and manipulating data and it is undertaking a wide range of analyses to enhance understanding of air pollution (Carslaw & Ropkins, 2011). For air pollution studies, R represents the ideal system with which to work. Core features such as effective data manipulation, data/statistical analysis and high quality graphics lend themselves to analyse air pollution data (Carslaw, 2014).

### 3.4 Data Analysis

Ambient air pollution concentrations were analysed daily and every month on the region and type of pollutant. The motive of conducting a study over different months of the year was to see if there were any seasonal effects that could affect or harm the health of persons living or working in these areas as a result of exposure to the factors under investigation. The permanent

AQ monitoring stations analysed ambient $SO_2$ and $PM_{10}$ and, through satellite data, exceeded national ambient air quality standards were identified using geographic information systems (GIS).

The use of monthly, seasonal and annual data analysis of $S0_2$ data permitted identifying diurnal patterns (variation) over the ten years to identify the occurrence of peak $SO_2$ exposures similar to a study conducted by Sangeetha et al., (2017). This analysis was only possible for $SO_2$ caused by its sampling interval of 10-minute averages, compared to a 24-hour gravimetric average for $PM_{10}$, as it is impossible to determine hourly variations.

The wind direction reported at air quality monitoring stations was provided to provide insight into the utility of employing nearby AQ monitoring stations as an intermediate of ambient air quality by examining how pollutant transportation direction affects the environment. Missing data was identified as a result of the instrument and or power failure. These occurrences were labelled as such, and the resulting data was cleaned to exclude data with negative, missing, or zero values from further analysis (Sangeetha et al., 2017, 2018).

A Vaisala Y50 sensor was used to monitor temperature and relative humidity, which was compared to an HMP45D temperature and humidity probe. During the equilibration periods, temperature and humidity differences induced changes in the weight of the filters, resulting in post-weighting of sampled filters having a lower mass than non-sampled pre-weighted filters (Brown et al., 2006). A stable laboratory environment was achieved by:

- All gaps between doors and windows in the gravimetric laboratory were re-sealed to guarantee an airtight seal at all entrances;
- All gaps between doors and windows in the gravimetric laboratory were re-sealed to ensure an airtight seal at all entries;
- The air conditioning system in the gravimetric laboratory was distinct from that in the more extensive laboratory;
- The macro-environment was monitored using electronic temperature and relative humidity monitors (Mecklenburg, 2007).

Seasonal distribution of $SO_2$ and $PM_{10}$ was also explored by generating monthly averages, which allowed for the discovery of seasonal variations, summer (December, January, February), autumn (March, April, May), winter (June, July, August), and spring (September, October, November).

$SO_2$ and $PM_{10}$ information were saved in Microsoft Excel in a Spreadsheet with a unique identification number, date, time, temperature, mugginess, and individual weights of filters for each weighting session and the sampler where it had to be delivered was labelled.

This study emphasized the pollutants $PM_{10}$ and $SO_2$, as these are pronounced in the study areas. These pollutants are generated by residential, agricultural, mining and power generation activities that are pronounced in the province of Gauteng. The available resources were also aligned with the collection of data for these two pollutants. The findings of this study can be compared to the available literature on $SO_2$ and $PM_{10}$ pollution.

Previous work by Omer (2008) indicated a relationship between relative humidity, temperature and the concentration of $PM_{10}$ and $SO_2$. Their work concluded that humid conditions partially convert $SO_2$ to acidic solutions, and $PM_{10}$ gradually cements together, caused by the moisture. These activities lead to reduced concentrations of pollutants. Temperature, on the other hand, is one of the drivers and distributors of dispersed contaminants. It is notable that the temperature/pressure relationships also affect the overall level of the concentrations. However, $SO_2$ concentrations increase with temperature at constant humidity levels (Lou et al., 2017).

Work conducted by Moja & Godobedzha (2019) on spatial and temporal assessment of $PM_{10}$ levels within the City of Tshwane in South Africa focuses on the meteorological conditions and their importance in evaluating the impacts of sources on surrounding areas, as they dictate the transportation, dilution, and dispersion of contaminants in ambient air. Wind patterns, clouds, rain, and temperature can all affect the weather.

The relationship between $PM_{10}$ concentrations and wind speed shows which high concentrations dominate wind directions, and also highlights the probability that corresponds well with the location or dominant source likely to be a traffic source, a commercial area, residential fuel burning, especially around the station, as well as long-range pollution, again caused by traffic sources and the commercial regions.

# CHAPTER 4: STUDY OF $SO_2$ OVER THE CITY OF TSHWANE USING TEN YEARS OF GROUND-BASED DATA

## 4.1 Introduction

Air pollutants caused by sulphur dioxide ($SO_2$) has grown to be an essential concern as it has a significant effect on the environment and human health. Environmental impacts include corrosive acid deposition and airborne sulphate aerosol. In contrast, health effects on human health include chronic obstructive pulmonary diseases (COPD) (Ghozikali et al., 2015) and asthmatic attacks in young children (Clark et al., 2015). During the last few decades, the developing countries in Asia made strides to improve the global $SO_2$ emissions by 60% due to the rapid industrial growth (Smith et al., 2011). African countries contribute about 5% of the total global $SO_2$ emissions, extending to about 30% by 2030 (Liousse et al., 2014).

South Africa is a developing country rich in coal mines, with innovative industrial growth still facing air pollution challenges. The main percentage (93%) of electricity generation is fundamentally based on coal-based power plants in the country (Menyah & Wolde-Rufael, 2010) due to the considerable coal reserves that release about 1.5 million tons of $SO_2$ annually (Lloyd, 2002). Nearly 95% of electrical-related technology in the country is owned by the power giant ESKOM, and about 5% is maintained by municipalities and private sectors (Pretorius et al., 2015; Spalding-Fecher & Matibe, 2003). The health affecting pollution outflows from these municipality owned power stations might be more than that from ESKOM, as they predate the power giant (Spalding-Fecher & Matibe, 2003). Subsequently, to gain proper perception of $SO_2$ distribution over a particular region, continuous monitoring and reporting of air quality data is integral for effective air quality management practices and to ensure that the pollutants are maintained within the standards (Macpherson et al., 2017). Accurate mapping of regional air quality is essential for sound environmental mitigation and monitoring planning (Hamm et al., 2015).

Over the years, meteorological assessments have been carried out in a number of countries. Rainfall, temperature, and humidity, according to Gounden (2006), are essential meteorological characteristics that have a significant impact on the daily concentration of $SO_2$ in the Durban area. He also came to the conclusion that meteorology has a consistent pattern of impacting air pollution, with higher concentrations of pollutants during winter months (with frequent inversions) than during summer months (effects due to the absence of vertical mixing). Unal et al. (2000) investigated principal component analysis (PCA) and multiple regression analysis techniques to see the correlation between $SO_2$ concentrations measured at Istanbul's European and Asian areas and meteorological parameters during two winter periods. The results suggested that the most critical parameters, highly correlated with $SO_2$ concentrations in the Istanbul metropolitan area, are atmospheric pressure and surface zonal and meridional winds. Venter et al. (2012) conducted a 24-month study from 2008 to 2010. The study focused on the air quality in the Bushveld Igneous Complex of South Africa. Marikana in Northwest province was selected as the representative area and explored the industrial sources for $SO_2$ emissions. A comprehensive interpretation was drawn from the study but not a complete representation of $SO_2$.

Sangeetha. (2017) studied seasonal, inter-annual variations of sulphur dioxide ($SO_2$) in Sharpeville. The results showed that the seasonal variations of $SO_2$ demonstrated that Ground-Based and OMI satellite-derived measurements followed a general pattern of the increasing trend from autumn until late winter and decreased from the start of spring; however, the latter showed exceptional high $SO_2$ levels in summer. Morakinyo et al. (2020) provided data on critical pollutant concentrations and trends in Pretoria West's industrial region. The $SO_2$ yearly mean in their analysis did not surpass the South African prescribed guidelines. The attention of the pollutants varied regularly, with $SO_2$ reaching its maximum and lowest levels throughout the night and day hours, respectively. Also, $SO_2$ presented the highest levels in winter and the lowest level in summer.

This study aims to investigate meteorological factors of $SO_2$ derived from ground-based data over three monitoring air monitoring stations (namely Mamelodi, Rosslyn and Pretoria West) in Tshwane, South Africa, over ten years. This section focuses on temperature, humidity, rain, wind direction, wind speed, and seasonal variations in meteorological variables and $SO_2$ air pollutant concentrations measured at the three research sites.

## 4.2 Data Analysis

The earlier chapter has provided more explanation on the evaluations adopted from the procedures for data management, such as data coding, cleaning of data, and censoring of information to achieve the analysed dataset. Various guidelines regarding data handling needed to be followed as a significant aspect of the quality control and assurance procedures to guarantee a standardised information management approach, preventing any deviations from the written/proposed protocol.

In this section of the study, data will be analysed and the results from the database and scientific concepts used in environmental and pollution management science will be used to draw conclusions. The study assumed that using average concentrations over the longitudinal period that the data was captured would be the desirable representation of the pollutant concentration in the atmosphere. The average concentrations were computed and assumed as the values of the highest probability. In cases of pronounced variations for $SO_2$, it was assumed that the higher the variation, the more seasonal the $SO_2$ vary in a studied area.

This chapter discusses the findings regarding the causes of air pollution in the City of Tshwane, Gauteng, and the effects of the pollutant concentrations on human health and the environment in the Mamelodi, Pretoria West, and Rosslyn research areas. The study was based on the analysis of monitoring data and the modelled results simulated by Aeronet and SAWS.

## 4.3 Results

The meteorological parameters (wind speed, wind direction, temperature, humidity and rainfall) and $SO_2$ data from three ground-based monitoring sites are presented here. This section includes the results and discussion of the findings obtained during the study.

### 4.3.1 $SO_2$ variations in the City of Tshwane

The average $SO_2$ concentration of each sampling area was computed from data and tabulated to evaluate how much the pollutant contributes to the overall summation of the composition in ambient air and determine concentrations of major pollutants in the City of Tshwane area. Table 4.1 below presents the summarised version of the collected data, showing the average concentration of the $SO_2$ pollutant and the relative standard deviations of the data.

**Table 4.1: The average standard deviation, RSD, the maximum and minimum concentration of various pollutants in the City of Tshwane area**

| | $SO_2$ (ppm) | Wind Direction (deg) | Wind speed (m/s) |
|---|---|---|---|
| **Average** | | | |
| Rosslyn | 7,35 | 175,55 | 2,07 |
| Pta West | 10,83 | 157,4 | 1,98 |
| Mamelodi | 5,06 | 154,37 | 2,06 |
| Frequency/ Count | 26 229 | 38 931 | 38 975 |
| **Maximum** | | | |
| Rosslyn | 253,71 | 360 | 12,94 |
| Pta West | 811,48 | 360 | 26,9 |
| Mamelodi | 435,58 | 429 | 9,98 |
| **Minimum** | | | |
| Rosslyn | 3 | 0,032 | 0 |
| Pta West | 0 | 0 | 0,04 |
| Mamelodi | 0,03 | 0 | 0 |
| **Standard Deviation** | | | |
| Rosslyn | 8,77 | 98,05 | 1,23 |
| Pta West | 19,15 | 104,04 | 1,71 |
| Mamelodi | 7,25 | 94,89 | 1,16 |

### 4.3.2 Monthly variation of $SO_2$

The monthly mean fluctuations of $SO_2$ trends, as well as the frequency distribution of air quality conditions over the City of Tshwane's Mamelodi, Rosslyn, and Pretoria West monitoring stations, were meticulously analyzed throughout ten years (2009 to 2018) and are presented in figure-4.1.

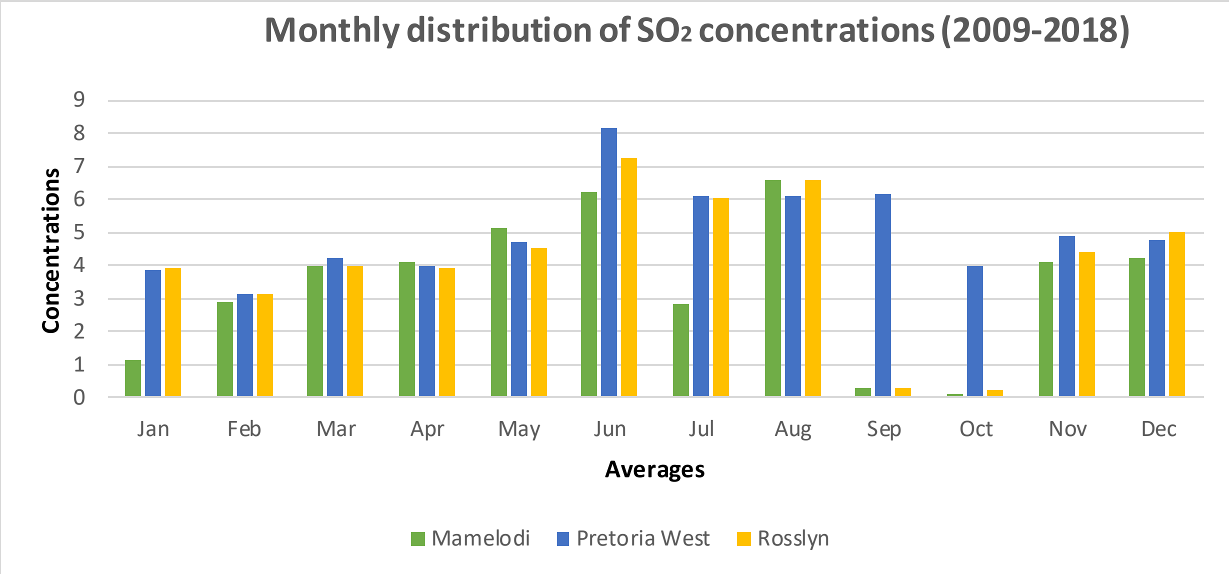



**Figure 4.1: Distribution of $SO_2$ concentrations across the three sites from 2009 to 2018.**

The monitoring stations show similar patterns with variations for January, September and October over Mamelodi and in September and October for Rosslyn, although the intensity of the monthly contributions to those trends differs and, in some cases, significantly so. These results are associated with land use, meteorological factors and activities in the area. Figure 4.1 highlights these trends.

The observation reflects that the monthly mean of $SO_2$ concentrations recorded at the three stations ranges from a low of 0.2µg/m³ in Rosslyn and Mamelodi to a high of 8.1µg/m³ observed in Pretoria West. The monthly mean in the monitored system does not exceed NAAQS' annual limit of 50µg/m³ in these stations. However, noteworthy differences occur between the stations.

The highest concentrations of $SO_2$ are observed during June, July and August (winter); this agrees with the study conducted by Sangeetha & Sivakumar (2019), where they also observed high concentrations of $SO_2$ emissions during the winter months. The high concentrations could be from coal-fired power plants, increased household combustion in the winter months and traffic emissions (Josipovic et al., 2010).

### 4.3.3 Seasonal Variations of $SO_2$

The seasonal variations of $SO_2$ demonstrate an increasing trend for the emergence of $SO_2$ from the start of autumn until late winter and a decreasing emergence trend from the beginning of spring.

The seasonal variation of the sulphur dioxide ($SO_2$) pollutant in the three stations shows that the winter months recorded the highest pollution rates of $SO_2$. The higher incidence during the winter months instead points to coal fires being used for residential heating and cooking during the winter months in the low-income residential areas and the informal settlements.

The seasonal variation shows how air pollution's harmful impacts can still be experienced long after factories, plants, or power stations have ceased operating. Besides other highly-industrialised areas, this impact is also apparent in the City of Tshwane, where industrial areas and their emissions or pollutants become a significant environmental challenge for the city (Wernecke et al., 2015). Since many of these factories do not have the means to change their operations to become fully compliant, many plants or factories do as little as possible to control their $SO_2$ emissions. Therefore, South Africa’s adherence to the emission standards is among them the weakest in the world. All the $SO_2$ generated during coal burning goes into the air (Myllyvirta, 2021). However, it is not the only industry that contributes to such high levels of air pollution. Because of poverty and no access to electricity, most households in the disadvantaged communities still use coal to heat their homes in winter or cook their meals, thereby contributing to the high $SO_2$ emissions, especially in the cold winter months. These findings correlate with the observations where the winter/colder months reported much higher volumes of $SO_2$ emission.

In addition to high $SO_2$ levels caused by household pollutant emissions or industrial emissions, polluted air emissions incorporate uncontrolled and controlled discharges, and these can cause high concentrations of $SO_2$ released into the atmosphere. As observed by (Mathee & von Schirning (2003), uncontrolled sources of pollution are open tyre fires, which result in inadequate ignition, and pollutants are discharged into the environment.

### 4.3.4 Background meteorological conditions

#### (a) Wind direction and wind speed in the City of Tshwane

$SO_2$ levels are measured routinely in numerous cities throughout the world. Still, caution is required to ensure that observations from the monitoring networks set up for reasons other than those observed in the present study are suitable for evaluating health risks. Averaging periods of 24 hours are commonly used in short-term exposures; however, under certain conditions, even shorter periods are required (hour). For long-term exposures, the annual means based on a series of daily observations might be satisfactory.

The wind rose figures indicate the general direction and speed during the sampling or observation period. North-westerly winds were prevalent during observation, meaning the focus of most of the $SO_2$ pollutants was south-east.

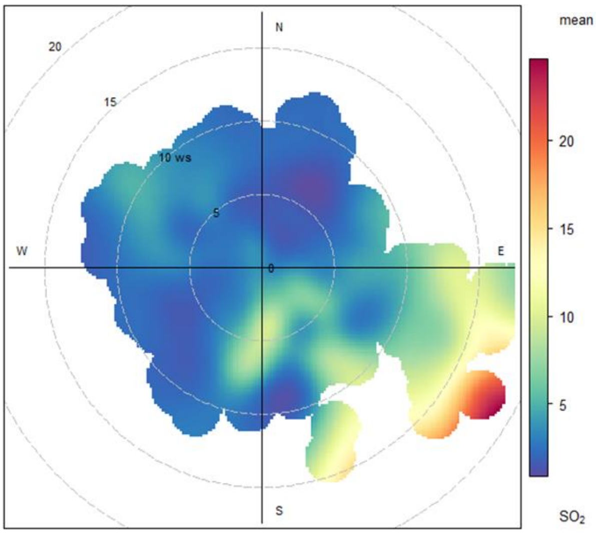



Figure A: Mamelodi $SO_2$ Polar Plot

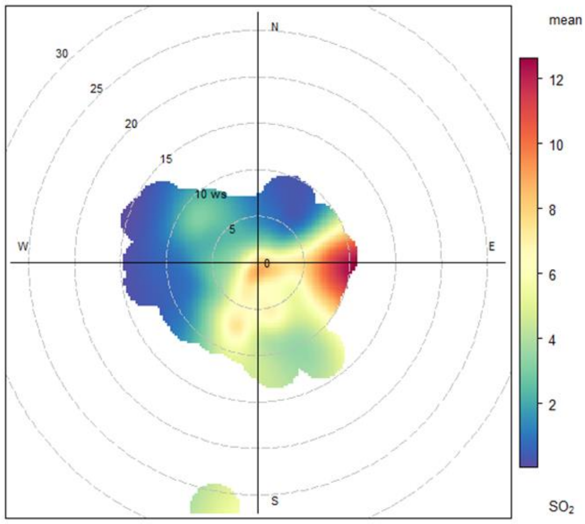



Figure B: Pretoria West $SO_2$ Polar Plot

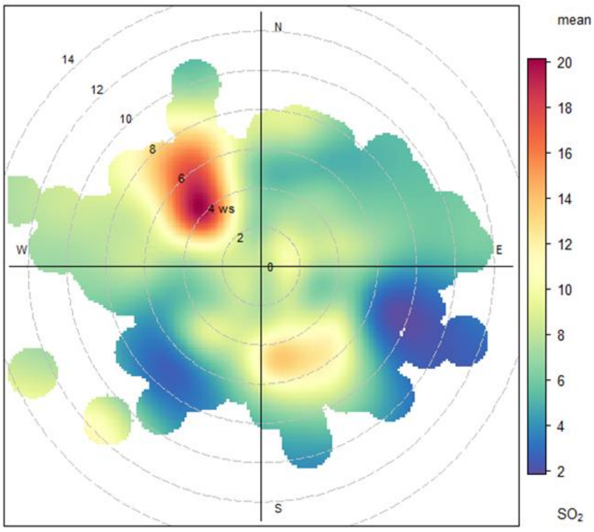



Figure C: Rosslyn $SO_2$ Polar Plot

**Figure 4.2: Polar Plots showing wind speed and direction effects on $SO_2$ at the Mamelodi, Pretoria West, and Rosslyn monitoring stations in the City of Tshwane.**

The Mamelodi polar plot shows the higher concentrations of $SO_2$ and moderate winds (ranging from 5-8m/s) blowing from the north-west. The high $SO_2$ concentration in the south-eastern quadrant indicates the highly polluted low-cost residential areas in Mamelodi.

The polar plot for $SO_2$ concentrations at Pretoria West shows a hotspot associated with periods of high wind speed (>6m/s) in eastern quardrant with winds blowing from the north-west region. A hotspot in the eastern area, approaching Pretoria's central location, can be seen on the polar plot, this indicates a high pollution level in the area due to traffic sources, tall stacks and industrial activities respectively.

In Rosslyn, the polar plot shows a potential source of high concentration of $SO_2$ in the north-western area as well as the south-eastern area. The wind direction corresponds with the location of the low-income residential areas and the high level of industrial activities in the area.

Prevailing winds are to the south-eastern direction of the city, with moderate to high winds observed. High concentrations of $SO_2$ can be observed in areas with low residential regions, traffic sources and industrial areas, this may be due to biomass burning.

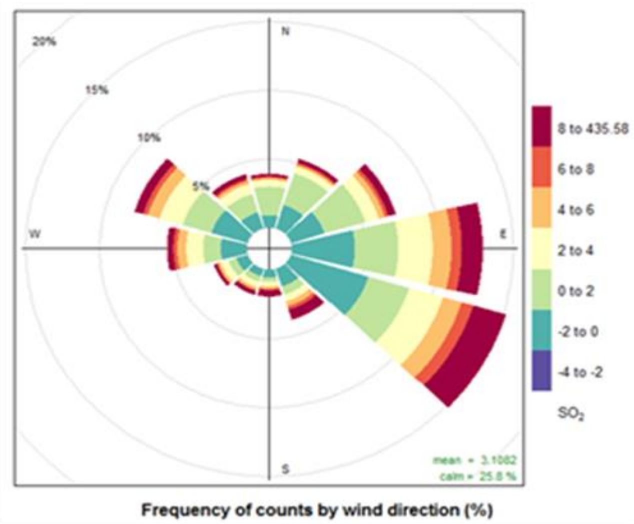



*Figure A: Mamelodi $SO_2$ Pollution Rose*

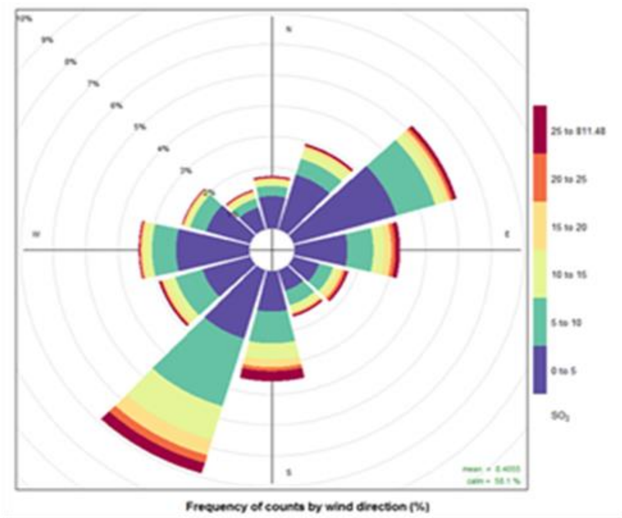



*Figure B: PTA West $SO_2$ Pollution Rose*

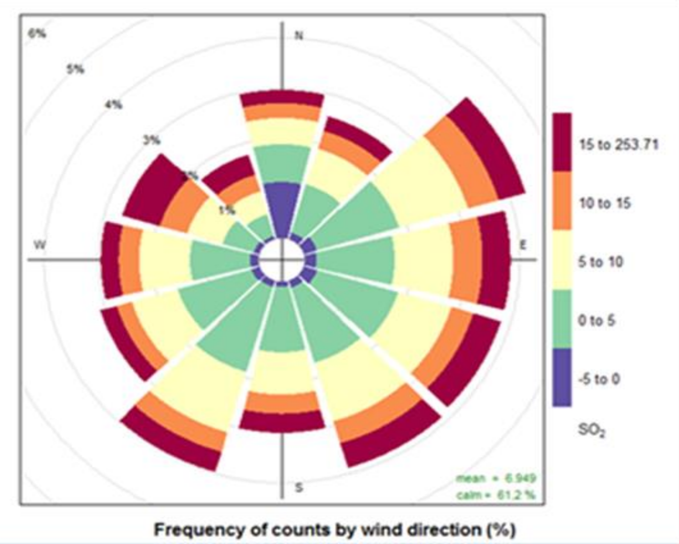



*Figure C: Rosslyn $SO_2$ Pollution Rose*

**Figure 4. 3: Mamelodi, Pretoria West and Rosslyn $SO_2$ wind speed and direction.**

**(b) Temperature, Humidity and Rainfall**

The air pollutant concentrations in the City of Tshwane are closely linked to the meteorological parameters. This study analysed the relationship of $SO_2$ concentrations with meteorological factors such as temperature, relative humidity, and rain (precipitation) in 2009 to 2018 using annual averages. According to the results obtained through the data analysis, higher $SO_2$ concentrations are strongly related to higher pressure systems, lower temperatures, somewhat lower precipitation and higher relative humidity.

In this study, the variations of the average daily temperature for each month were plotted from January to December.

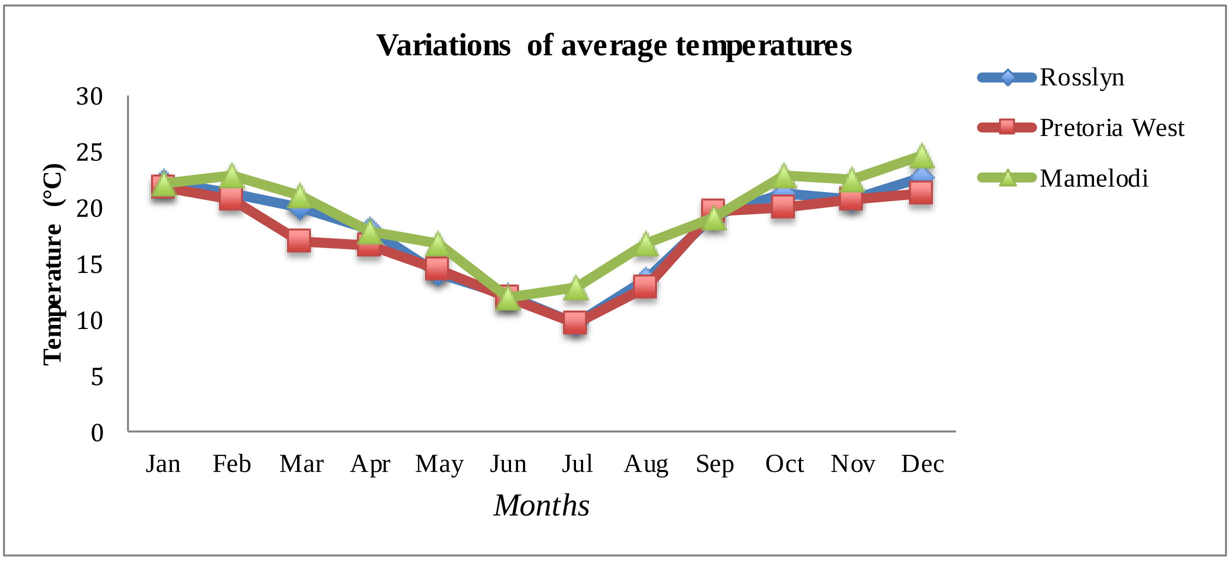



**Figure 4. 4: Monthly variations of average temperatures observed from 2009 to 2018**

From Figure 4.4, it is evident that the monthly average temperatures measured at Mamelodi, Rosslyn, and Pretoria West range between 10 and 23°C. It is also apparent that all three measured stations have similar annual ambient temperature conditions. The data also suggests that all three stations experience the coldest temperatures between June and August in the year, as predicted by the minima in the ambient temperature curves. In South Africa, these months represent winter and are the coldest months in the southern hemisphere. The figure shows moderate temperatures for March to May (autumn) and September to November (spring). The warmest season is December to February (summer), although Mamelodi tends to be slightly warmer from October onwards.

A comparison of ambient temperatures between the three monitoring stations was conducted. The results (as shown above) indicate that there is overall no significant difference in the mean temperatures between Mamelodi, Rosslyn and Pretoria West.

The summarised data provides a picture of the temperature variations in the winter and summer months. When analysing the temperature values per annum, it can be observed that there are fluctuations in the winter and autumn temperatures (low temperatures) and increases in the spring and summer values (high temperatures) (Leszek-Rogalski et al., 2014). Lower temperatures cause a high concentration of $SO_2$ in the atmosphere.True to this study, lower temperatures caused an increase in $SO_2$, this is due to atmospheric stability with frequent inversions. These findings are similar to the findings reported by Kalbarczyk & Kalbarczyk (2007). These findings are also similar to the earlier findings that stated higher $SO_2$ concentrations are strongly related to colder temperatures.

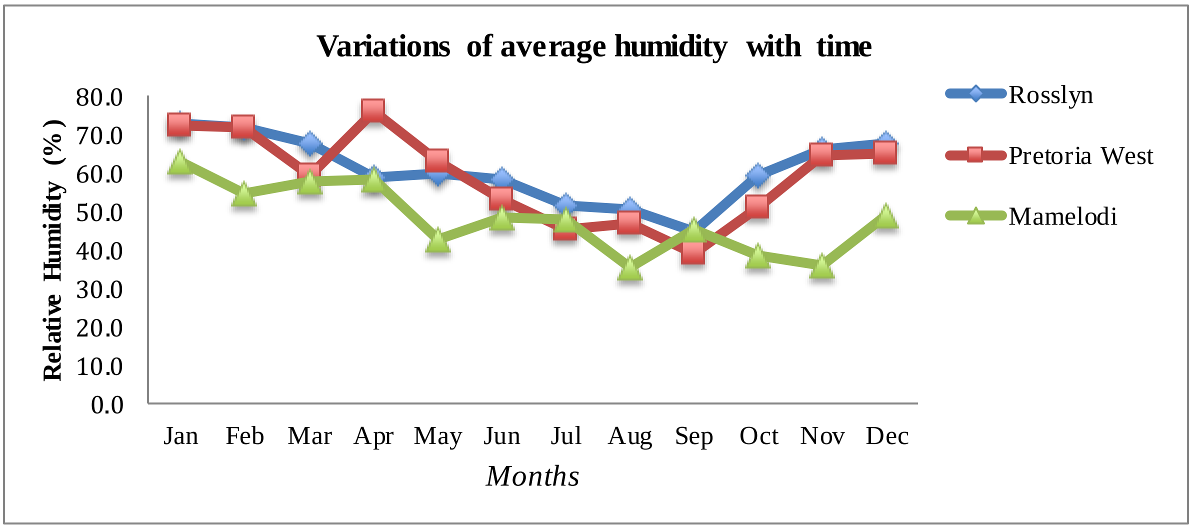



**Figure 4. 5: Monthly variations of average humidity obtained from the period 2009 to 2018**

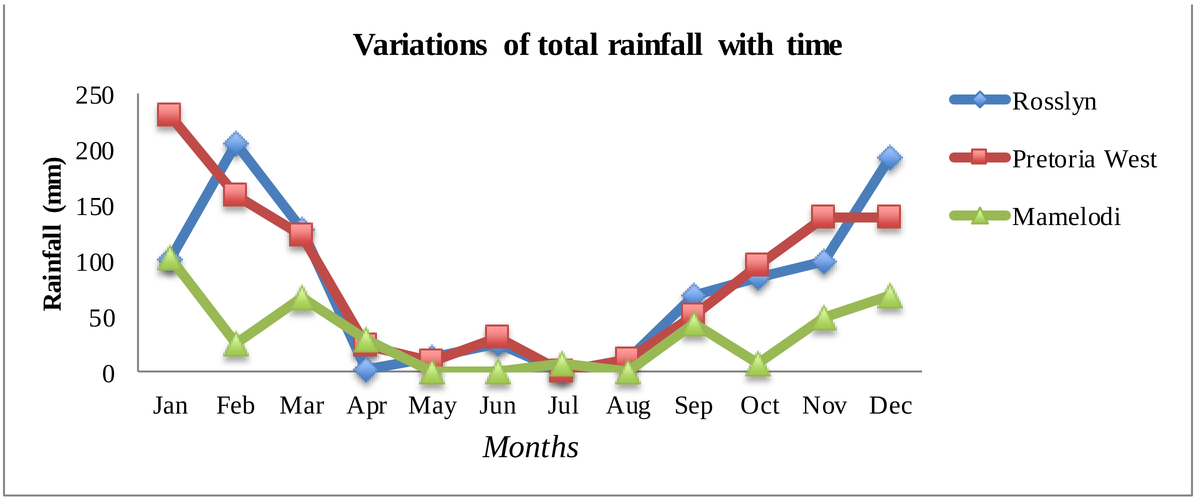



**Figure 4. 6: Monthly variations of total rainfall obtained from the period 2009 to 2018**

Figures 4.5 and 4.6 present relative humidity and rainfall. The relative humidity values of less tha 60% are associated with low rainfall values <100 mm. The months with higher humidity averages of >60% report higher rainfall levels, a finding that is in agreement with the work by Sposito et al. (2017). It is noteworthy that Mamelodi has significantly lower rainfall levels and humidity levels than the other two sites, despite all three sites being situated south of the Magaliesberg Mountain range.

If $SO_2$ concentrations are constant, meteorological quantities are expected to influence the values. For example, lower temperatures may cause higher $SO_2$ concentrations because of an increase in the overall volume of $SO_2$. Temperature levels also affect air density, and the thickness of ambient air can influence the affinity of pollutant particles to floating in the atmospheric air. According to the results obtained in this analysis, higher $SO_2$ concentrations are strongly related to lower temperatures, lower precipitation and higher relative humidity, this was also confirmed in earlier studies by Turalioğlu et al., (2005).

When released into the atmosphere and mixed with water, sulphur dioxide can react to form acid rain, according to the following reactions:

$SO_2 + OH \rightarrow HOSO_2$

$HOSO_2 + O_2 \rightarrow HO_2 + SO_3$

$SO_3\ (g) + H_2O\ (l) \rightarrow H_2SO_4\ (aq)$

or

$SO_2\ (g) + H_2O \leftrightarrow SO_2H_2O$

$SO_2\ \ H_2O \leftrightarrow H^+ + HSO_3$

$HS\ O_3^- \leftrightarrow H^+ = SO_3^{2-}$

Sulphur dioxide has a direct harmful impact on human health and is responsible for various respiratory diseases. Like most air pollutants, sulphur dioxide poses a more significant threat to sensitive groups such as the elderly, asthmatics and children. By contributing to acid rain, sulphur dioxide can also significantly have detrimental impacts on plants, surface waters, and buildings. While sulphur dioxide has harmful health effects, acid rain, while harmful to plants and the environment, is not considered to have direct negative human health impacts (United States Environment Protection Agency, 1997).

### 4.3.5 Effect of $SO_2$ on human health and the environment

Emissions of $SO_2$ have been studied extensively, but many questions remain about the impact of $SO_2$ emissions on human health (Wark et al., 1998). Few epidemiological studies have examined the effects of individual pollutants on human or animal health because $SO_2$ tends to occur in the same kinds of atmospheres as particulate matter and high humidity.

$SO_2$ is an acidic gas that forms acid rain when it comes into contact with moisture. The acidic solution has a low pH value with a cutting effect that causes the disintegration of salts and carbonates that form the chemical structures of certain materials in the environment. Acidic solutions also cause human, animal and plant tissue irritations and burns, making $SO_2$ an environmentally threatening gas.

High concentrations of $SO_2$ may result in temporary breathing impairment for asthmatic children and adults and those active outdoors (United States Environmental Protection Agency, 1997). National and local government departments, especially the departments and other institutions responsible for the citizens' health in South Africa, are increasingly concerned about the impact of air pollutants on the health of the country's citizens. In turn, strategies to reduce, limit and control pollution have been formulated, and limits to levels of concentration in the ambient air are set as guidelines. The authorities have also recognised that the adverse effects caused by pollutants on human health have to be included in the formulated standards, regulations or laws. For example, harmful environmental factors such as pollution will disrupt the normal function of the ecosystems, weather, and climate. They will have long-term adverse effects on the country's healthcare costs and the costs resulting from the damage to the environment. Typical products include, but are not limited to, global warming or, more appropriately, climate change, caused by the rise in the levels of greenhouse gases, and acid rain caused by $SO_2$ and other acidic gases that cause erosion of soils and carbonate structures.

The WHO (2018) researched the air pollution or contamination of the air in the City of Tshwane and revealed that the measured pollution has caused and will continue to cause significant diseases among the people living in the area. Most $SO_2$ emissions occur in winter, in most cases caused by domestic biomass/coal burning and domestic fuel burning. Low-income households and informal settlements depend on domestic fuel such as coal, paraffin and wood for cooking and heating purposes. Although the significant route of $SO_2$ absorption into the human body occurs through the intestinal tract, the respiratory tract is the weakest organ and is easily affected by airborne materials. Most studies on humans and animals have shown that the upper respiratory tract absorbs between 40% and 90% of inhaled $SO_2$. When the $SO_2$ has reached the bloodstream, it tends to become widely distributed throughout the body, is metabolised, and excreted using the urinary tract. However, the most critical damage by the $SO_2$ that has been inhaled is done to the lungs. $SO_2$ had a negligible effect on human respiratory capacity at a concentration of 2.1 $mg/m^3$ (0.75 ppm), but not at 1.1 $mg/m^3$ (0.37 ppm), whereas sulphuric acid mist has an effect on respiratory capacity at levels as low as 0.35 $mg/m^3$. Joint exposure to $SO_2$ and ozone has been shown to have synergistic effects on pulmonary function.

Effects of exposure to $SO_2$ or sulphuric acid fog have been observed in mine workers. A concentration of 2.0 mg/m3 of sulphuric acid fog irritates the throat and nose, whereas a value of 1.4 mg/m3 has no effect on pulmonary function. However, the effects of this pollutant are also closely dependent on the size of the particles.

Some of the $SO_2$ may constitute emissions of substances through secondary reactions to produce other toxic industrial by-products and sulphur-containing chemicals, including the emissions causing acid rain. Chemically engineered technologies should be put in place to suppress the emission of $SO_2$.

# CHAPTER 5: STUDY OF $PM_{10}$ OVER THE CITY OF TSHWANE USING TEN YEARS OF GROUND-BASED DATA

## 5.1 Introduction

Fine particulate matter ($PM_{10}$) is becoming a pollutant of interest within the air quality and health communities. $PM_{10}$ requires more investigations to quantify ambient concentrations in the South African context (Wright et al., 2011). The value of morbidity and mortality related to air pollution caused by particulate matter are high, and a recent World Health Organization (WHO) study estimated a cost of over US$3 trillion for the European Organisation for Economic Co-operation and Development (OECD) $PM_{10}$ can enter the respiratory system, and the unique size fraction deposit at various levels within the body (WHO, 2015).

$PM_{10}$ in the atmosphere has both natural and anthropogenic origins (WHO, 2015). Naturally occurring particulate matter results from windblown dust, volcanoes, biomass burning, and other naturally occurring phenomena. Anthropogenic sources of particulate include industrial combustion processes, vehicle emissions, waste incineration, domestic fuel burning, and mining.

$PM_{10}$ can be found in the atmosphere as solid or liquid particles with a variety of chemical compositions and sizes (Beckett et al., 1998; Kampa & Castanas, 2008; Harris et al., 2014). Particles are classified as primary or secondary contaminants. Except for chemical composition variations, primary particles are discharged directly into the environment from the supply. Simultaneously, secondary particles are generated in the atmosphere as a result of gas oxidation processes (Held et al., 1996; Hueglin et al., 2005; Beckett et al., 1998).

Biomass burning (veld fires), automobile exhaust emissions, industrial activity, domestic biomass burning, crushing and screening of materials, material handling operations, vehicle dust emissions on unpaved roads, and wind erosion of uncovered areas are all critical anthropogenic sources of particulate matter in the city of Johannesburg (City of Johannesburg, 2008; Oguntoke et al., 2013).

According to Brauer et al. (2012) & Burnett et al. (2014), new evidence on exposure-risk information and improved global exposure estimates promote higher exposure to ambient $PM_{10}$ than initially estimated (WHO, 2014a). An unnecessary fraction of the direction leading to these health impacts occurs in cities due to the higher density of human activities and air emissions. However, according to the Tshwane region, high emissions can also appear from domestic fuel burning in informal settlements, rural or peri-urban areas, particles associated with long-range transport, or a high prevalence of natural dust. Due to growing populations, growing urbanization and economic growth, these health impacts may also worsen in most of the world if not enough action is taken. Initial analyses are confirming this fact (WHO, 2014a, WHO, 2014b).

$PM_{10}$ is presently considered the best indicator of ambient air pollution health effects (Burnett et al., 2014, WHO, 2014a). Many human activities that contribute to ambient $PM_{10}$ also contribute to climate change and other health impacts (Karagulian et al., 2014). Mukherjee & Agrawal (2017) conducted a study that showed that road traffic and combustion of fuels are significant sources of particulate matter pollution. The study concluded that identifying possible sources and their control with regular epidemiological monitoring could help decrease particulate matter pollution. It is vital to understand the sources and activities contributing to local levels of ambient air pollution to reduce exposure to air pollution and hence the associated health impacts. For this reason, there is a growing number of regional studies that focus on the contribution of sources to air pollution levels, most often at the town level. Such studies consider several pollution sources, such as industrial actions, transport, biomass burning/residential activities, re-suspended dust, sea salt and different unspecified pollution sources of human origin.

There is strong evidence that most of the communities in Tshwane are exposed to high levels of pollution during winter and daily during rush hours, mostly in residential areas. It can be concluded that anthropogenic activities in the city are critical contributors of $PM_{10}$, with high levels more enhanced by meteorological/weather conditions, especially for those living in low-cost residential areas.

However, there have been recent improvements in the overall national air pollution levels registered at some of the country's air monitoring stations. This observation might be caused by the current Covid-19 pandemic that imposed a pause on human activity and reduced emissions of the pollutants usually caused by traffic or industrial activities. According to Venter et al. (2021), a reduction in ambient $SO_2$ levels and $PM_{10}$ concentrations was observed during the Covid-19 lockdown period causing a decrease in air traffic-related pollution.

This study uses the ambient air quality data from the three monitoring stations. The relationship between meteorological parameters and air pollutant concentrations of $PM_{10}$ recorded at the three sites (Mamelodi, Rosslyn and Pretoria West) in the City of Tshwane are presented in this chapter. Temperature, humidity, rain, wind direction, wind speed and seasonal variation concerning $PM_{10}$ in the City of Tshwane are the meteorological factors that are being investigated. The data analysed is from 2009 until 2018 in the City of Tshwane and synthesizing this information to estimate the main contributors of ambient $PM_{10}$ in the different sampling areas.

### 5.2 Data and Method of Analysis

Monitoring of ambient air pollution concentrations in the atmosphere provides valuable measurements that can be utilized to determine information on impacts and management. Monitoring data is limited to the location where measurements are taken and the radius of influence of the monitoring point on surrounding areas. Monitoring techniques for delicate particulate matter are essentially ground-based, and in South Africa, networks and sampling technology have progressed significantly in recent years.

The ambient air monitoring network of the City of Tshwane now consists of seven (7) permanent stations and one (1) mobile station, with this study focusing on three of the stations. These monitoring stations are strategically located to assess compliance with the national ambient air quality standard by monitoring the effects of industrial, traffic, and residential activities on ambient air quality.

Data was collected to suggest solutions to help minimise the impact of air pollution, to establish the causes of air pollution in the City of Tshwane, Gauteng, and to assess the effects of the concentrations of particulate matter ($PM_{10}$) in the area and the harm that these air pollutants cause to human health and the environment.

This study aims to investigate monthly averaged data (from 2009 to 2018) and the meteorological factors of $PM_{10}$ derived from ground-based data over three air monitoring stations (namely Mamelodi, Rosslyn and Pretoria West) in Tshwane, South Africa. The meteorological variables and air pollutant concentrations of $PM_{10}$ recorded at the three research sites are presented in the chapter, focusing on monthly mean, temperature, humidity, rain, wind direction and wind speed. The $PM_{10}$ concentrations in the sampled regions were measured using the R Studio Openair software to predict the results. . The software runs with the Interactive Data Language (IDL) and uses various algorithms for data processing to predict results (Carn, 2011). The data was requested from the South African Air Quality Information System (SAAQIS) hosted by South African Weather Services (SAWS). Missing values indicated that instruments were either faulty or not operational during some of the data sampling days. The summary plot (see in the appendix) shows the chosen variable (including $PM_{10}$) measurements that have meaningful records, indicating that the minimum in both is zero.

### 5.3. Results and discussion

Meteorological variables and $PM_{10}$ data from the selected Mamelodi, Pretoria West and Rosslyn monitoring sites were analysed and presented to demonstrate the Spatio-temporal variations of $PM_{10}$ concentration.

#### 5.3.1 Monthly mean distribution for Mamelodi, Pretoria West and Rosslyn

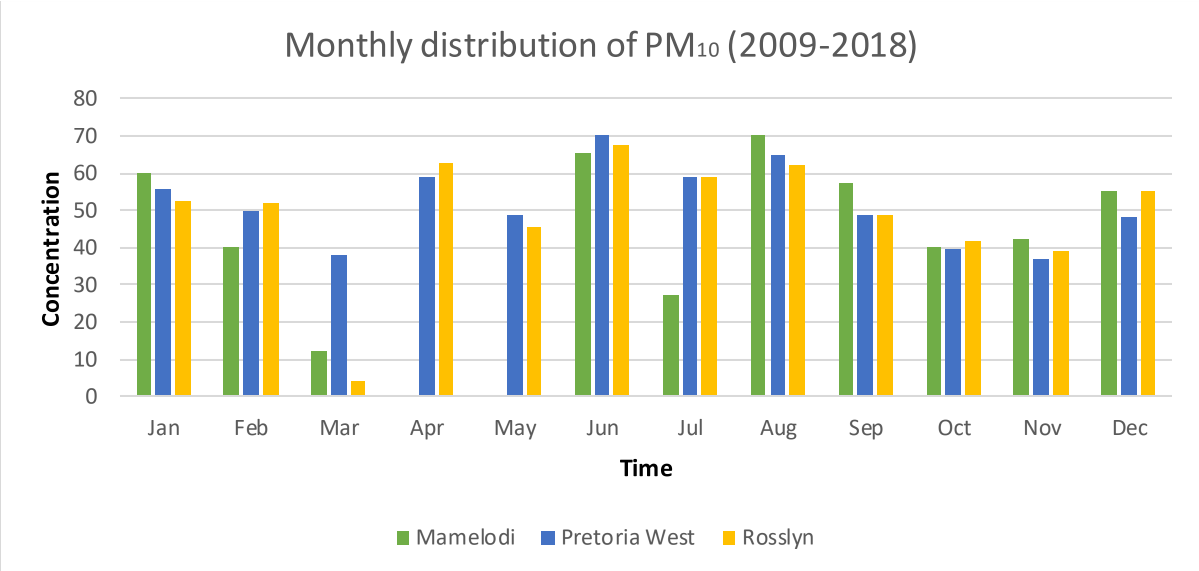



**Figure 5. 1: Monthly mean distribution of $PM_{10}$ from 2009 to 2018**

The monthly average concentrations of $PM_{10}$ were measured for Mamelodi, Rosslyn and Pretoria West stations of the City of Tshwane from 2008 to 2019. The results indicate that the observed monthly means of $PM_{10}$ concentrations ranged from 15 $\mu g/m^3$ to the highest standard of 70.0 $\mu g/m^3$. In March, April, May, and July, the monthly mean in the entire network surpassed the NAAQS annual limit of 40 $g/m^3$ (current) in all stations except Mamelodi. Particulate matter concentrations at the Pretoria West and Rosslyn stations are influenced mainly by pollution from low-income communities and industrial sources.

In terms of monthly trends, the average $PM_{10}$ concentrations at all three (3) sites in the city exhibit a strong seasonal feature. The highest monthly average concentrations were reported at Pretoria West (70 $g/m^3$) and Rosslyn (70 $g/m^3$) in June and August, respectively, while the lowest monthly concentrations were found at Mamelodi in spring, with recorded values below 10 $g/m^3$. The change in weather circumstances seen throughout winter and summer can explain the high and low monthly $PM_{10}$ concentration variations. Winter readings that are higher can also be linked to atmospheric stability and frequent inversions. The air in the unstable warm atmosphere rises to greater heights. However, because air sinks in a stable atmosphere, air contaminants spread horizontally in typical conditions. Dilution induced by the intense vertical exchange in the atmosphere, as well as precipitation and high temperatures that encourage dispersion, can explain the lowest numbers (Samson, P.J, 1988).

### 5.3.2 Seasonal Variations of $PM_{10}$

Particulate matter concentrations tend to vary with the changing seasons. More emissions are recorded in winter because of an increase in domestic coal and fuel burning. Biomass burning is a significant source of particulate matter and gas emissions in the atmosphere, and biomass burning tends to occur in the dry winter months in Gauteng, before agricultural activities in spring.

The $PM_{10}$ concentrations at the sampling sites indicate a distinct seasonal pattern, which can be explained by the changes in weather conditions seen throughout the winter and summer. The lowest results can be presented by dilution in the atmosphere, precipitation, and high temperatures that promote dispersion during the summer (January and February. The higher winter readings can also be linked to atmospheric stability, which is characterized by frequent inversions. It should be noted that the absence of access to power by the low-income households in these regions has caused these residents to have to utilise biomass and coal for cooking and during the winter months for heating. Thus, the reliance on such sources for heating and cooking and the continuous resultant air contamination are some of the reasons for the lifted $PM_{10}$ levels, which surpass the NAAQSs for most residential areas, and are of enormous concern regarding the wellbeing of these residents (Naidoo et al., 2014).

$PM_{10}$ values tend to fluctuate daily rather than on an hourly basis, in line with the detection limits of the meteorological analysis (Fonseca-Hernández et al., 2018). The plot for the monthly variations is identical to a multiplied action of the weekday plot. The monthly plots provide a broader spectrum and suggest that the overall annual averages would also produce a plot with a similar distribution, with the concentration of $PM_{10}$ peaking during June (cold, dry winter month, not much wind in Gauteng, and more significant residential heating taking place).

Minima and maxima are at critical hours when the concentrations are lowest between 6:00 am and 6:00 pm; this could be caused by factories starting work at 06:00 am, with motorists travelling to work, operations starting and industrial activities being at their peak (WHO, 2018). The maxima are reached between these "working hours". The weekday plots reveal a similar alignment of results, as there is likely more activity during the week and probably less over the weekend, as most of the workforce is perhaps off from work. The monthly plots show a maximum point in June (cold winter month), probably when industries are fully resourced.

The high levels of $PM_{10}$ recorded were caused by coal-fired power stations emitting high levels of pollutants during electricity generation (Kovac, J., 1996). Also, domestic fuel burning in low-income households and informal settlements contributed to the high levels of $PM_{10}$ (Naidoo et al., 2017).

These findings confirm that the concentration of $PM_{10}$ tends to be proportional to human activity, whether at work or home, and environmental scientists need to devise methods to mitigate the generation of micro dust, where feasible (Spiegel & Maystre, 2010).

### 5.3.3 Annual Mean

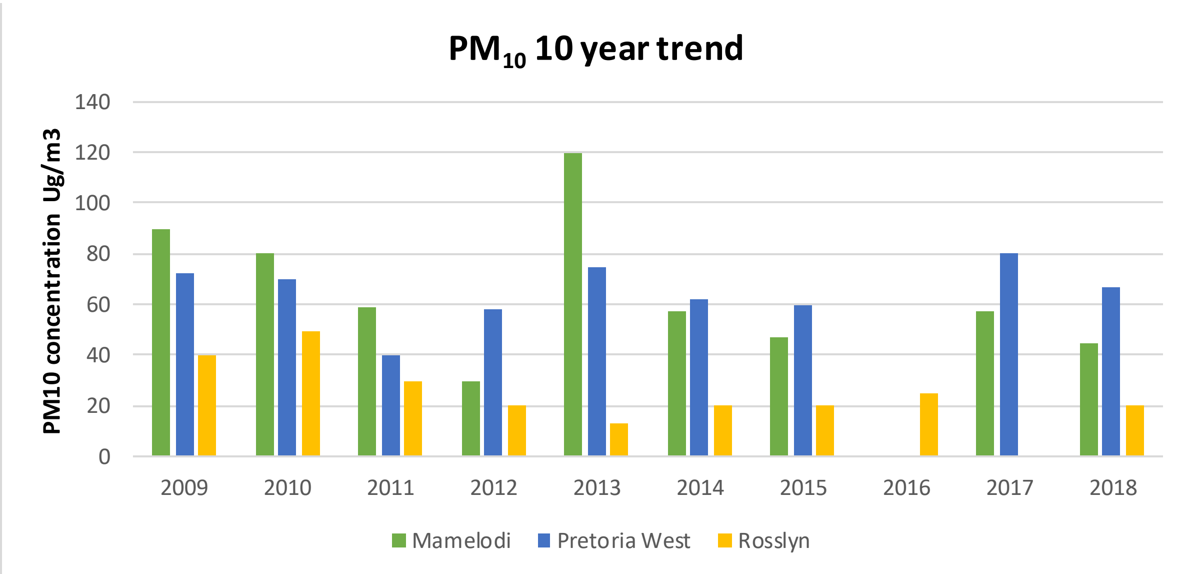



**Figure 5. 2: Annual mean distribution of $PM_{10}$ from 2009 to 2018**

Figure 5.2 shows the annual trends over the ten year sampling period at the three stations. The figure shows a stronger seasonal profile in the average $PM_{10}$ concentrations except for 2016 and 2017, where data was limited due to malfunctions at the monitoring stations.

The $PM_{10}$ concentration increase in winter and decrease in summer due to seasonal variation. The highest annual average concentrations were observed at Mamelodi. They were recorded above 120 µg/m³ during winter, while the lowest annual concentrations are observed at Rosslyn and with a value below 15 µg/m³ in summer. The difference in meteorological circumstances observed during the different seasons, such as rain, humidity, temperature, and pressure, can explain the high and low seasonal $PM_{10}$ concentration variations.

The yearly mean $PM_{10}$ concentrations measured across the entire network ranged from 13.00 g/m$^3$ in Rosslyn to 120.0 g/m$^3$ in Mamelodi. The annual mean in the whole network exceeded the National Ambient Air Quality Standard (NAAQS) annual limit of 50 µg/m³ (prior 2015) and 40 µg/m³ (current) in all stations except at the Rosslyn stations. These exceedances were mainly in the winter months due to more biomass burning, which increases ambient air pollution. The 2016 data gaps and anomalies were filtered out in order to obtain uniformity in the data sets. The reasons for the anomalies in the 2016 data are not discussed in this study which shall be addressed in the future.

### 5.3.4 Influence of background meteorological parameters

#### (a) Wind speed and wind direction concerning $PM_{10}$ in the City of Tshwane

As stated in chapter 4, the polar plot figures indicate the general wind direction and wind speed during the sampling period. $PM_{10}$ levels are routinely tested in numerous locations across the world. However, caution is essential to ensure that observations observations from monitoring networks established for a variety of reasons are also adequate for assessing pollution-related health concerns. The location of samplers and comparative sources, the surrounding topography, vulnerable populations, as well as the time-resolution of the observations, must all be addressed. Short-term exposures are typically averaged over 24 hours; however, certain scenarios, such as hourly exposures, necessitate shorter periods. Annual means based on a series of daily observations for long-term exposures.

Meteorological conditions are critical when analyzing the impacts of sources on the surrounding areas because they dictate the transport, dilution and dispersion of contaminants in ambient air. Wind patterns can affect how quickly pollutants move towards or away from a study site.

The plots below (Figure 5.2) indicate the winds that carry the majority of the $PM_{10}$ pollutant. It is observed the standard speed for $PM_{10}$ ranges between 4 and 6 ms$^{-1}$.

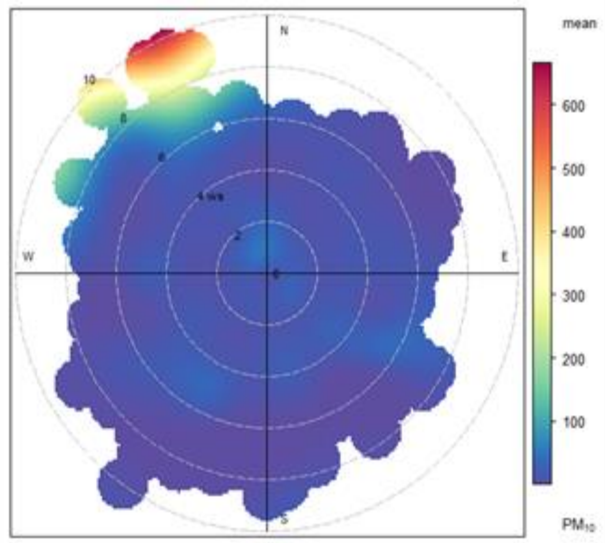



Figure A: Mamelodi $PM_{10}$ Polar Plot

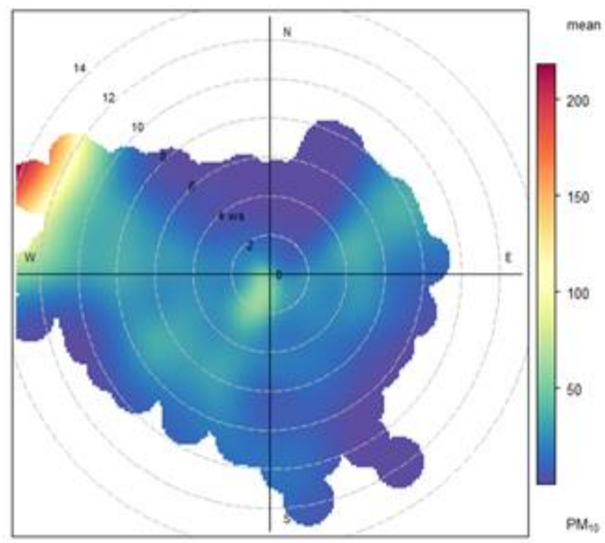



Figure B: Pretoria West $PM_{10}$ Polar Plot

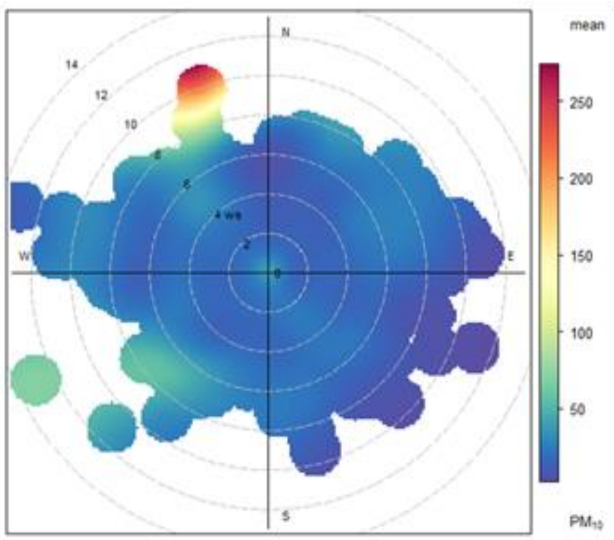



Figure C: Rosslyn $PM_{10}$ Polar Plot

**Figure 5. 3: Polar plot of $PM_{10}$ showing the effects of wind speed and wind direction on $PM_{10}$ in the three monitoring stations in the City of Tshwane.**

$PM_{10}$ concentrations are lowest in the north-east, south-east, and south-west quadrants when winds are low to moderate (varying from 0-4 m/s), with high concentrations of $PM_{10}$ in the north western regions. According to the Mamelodi polar plot, the north-west quadrant has high $PM_{10}$ concentrations, which coincides with the trend of low-cost housing, a commercial complex and open mining.

In Pretoria West, the polar plot shows a hot spot for $PM_{10}$ concentrations associated with periods of high wind speed (> 6m/s) in the north-west quadrant. The high $PM_{10}$ concentration is caused by the emissions from the low-income residential area and high traffic volumes, tall stacks, and industrial activities, respectively.

The polar plot in Rosslyn suggests a likely source of a high $PM_{10}$ concentration in the area to the north-west. In the south west, this wind direction corresponds to the presence of low-income residential neighbourhoods and industrial operations.

It is found that the north-west quadrant of The City of Tshwane is the area with the highest $PM_{10}$ concentrations, primarily due to low residential homes and industries in that part of the city.

**(b) Rainfall, Temperature and Relative Humidity Variations**

The effect of temperature, humidity and rainfall on air quality has to be noted, as some types of pollution are increased by the heat in summer, while others are enriched by cold winter weather.

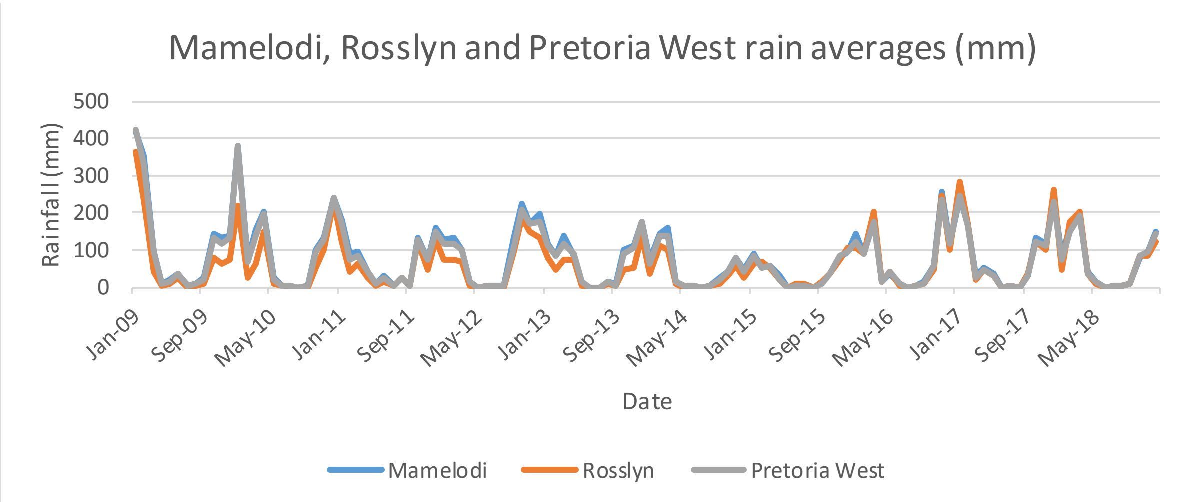
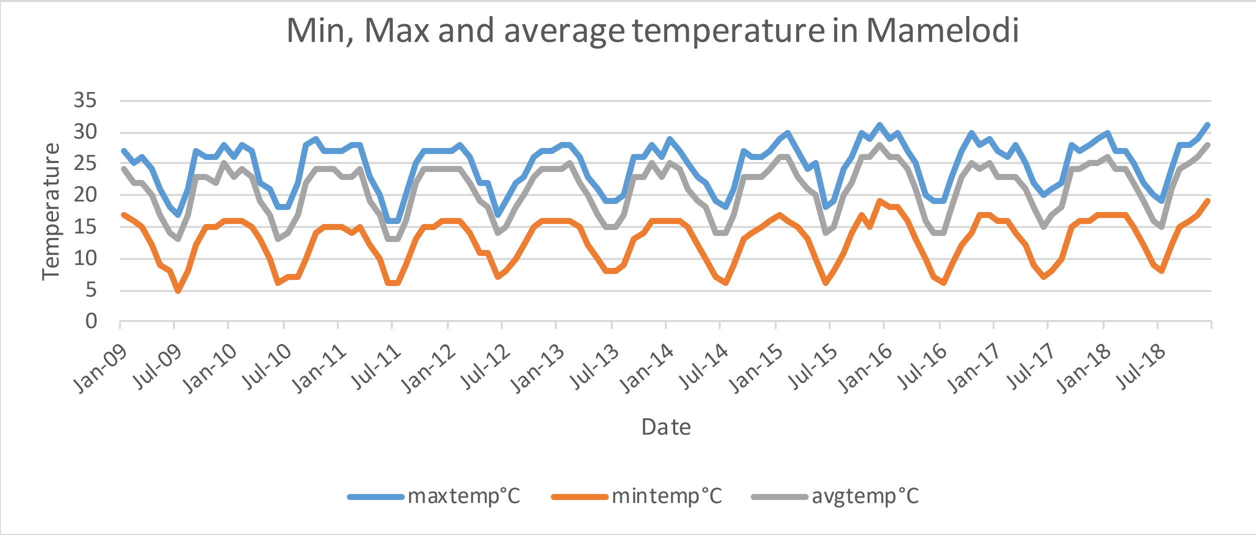


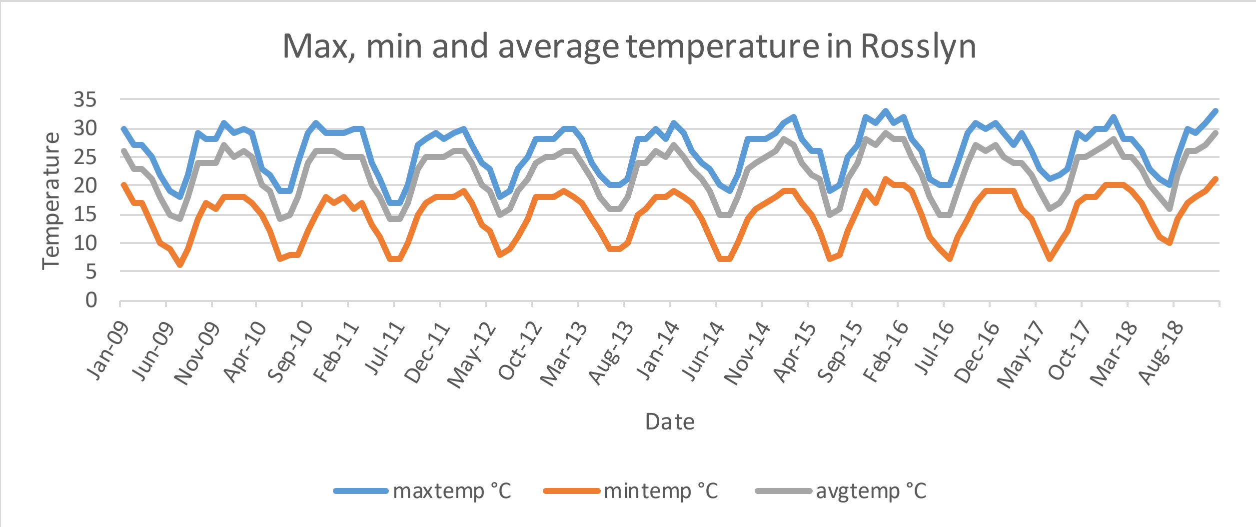

**Figure 5. 4: Temporal variation of accumulated daily rainfall for the three stations over the period from 2009 to 2018.**

The effect of rainfall on air pollution is significant. The highest rainfall months in Gauteng and specifically in the three sites were in January 2009 (421.81 mm) and in January 2010 (378.8 mm), as most rain falls in summer. As the January and February months are high rainfall months (is also noted in the earlier chapter, where monthly mean rainfall observations are indicated), there is a noteworthy improvement in the air quality during these months, as rainfall settles the dust and removes pollutant gases from the atmosphere.

The months of July each year recorded the lowest rainfall averages, and this is mainly based on the fact that July is the middle of winter, and the winter months are the dry months in Gauteng. Winter months have low precipitation, combined with the higher burning of coal for heating in the low-income residential areas and the burning of biofuels in the dry months; thus, these months yield higher values of $PM_{10}$ pollution in the air (DEA, 2012).

Interannual variability was used for the $PM_{10}$ because there is a high interannual variation in the $PM_{10}$ surface concentrations and pollutant deposition. Interannual variation contains a vital systematic component and is suitable for comparison between the years.



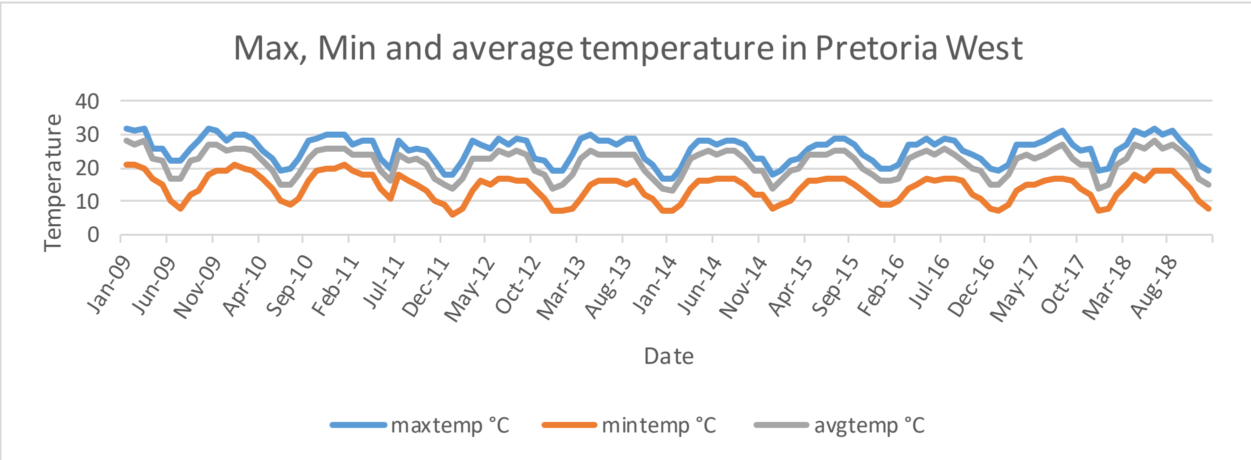




**Figure 5. 5: Min, Max and average temperature in Mamelodi, Rosslyn and Pretoria.**

Lower temperatures can be observed in winter and thus causing an increase in the $PM_{10}$ levels. Higher winter concentrations can be associated to atmospheric stability with frequent inversions. The lower $PM_{10}$ concentrations during the summer can be explained by dilution caused by intensive vertical exchange in the atmosphere as well as precipitation and high temperature that promote dispersion. These findings are in agreement with previous studies by Massey et al., (2012). The higher concentration of $PM_{10}$ in the Mamelodi, Rosslyn and Pretoria West urban areas are generally caused by more emission sources being prevalent in urban areas. Among other sources or causes, the $PM_{10}$ increases in the urban areas are also caused by heavy road traffic (cars) emissions and road transport (trucks) emissions (tyre pipe, brake wear, and re-suspension). (Dore et al., (2003) and Barlow et al., (2007) also stated in their studies that during the warmer summer months, emissions from the low-income residential areas should decrease considerably, as no heating is taking place that would have used coal, although they may still burn coal for their preparation of food.

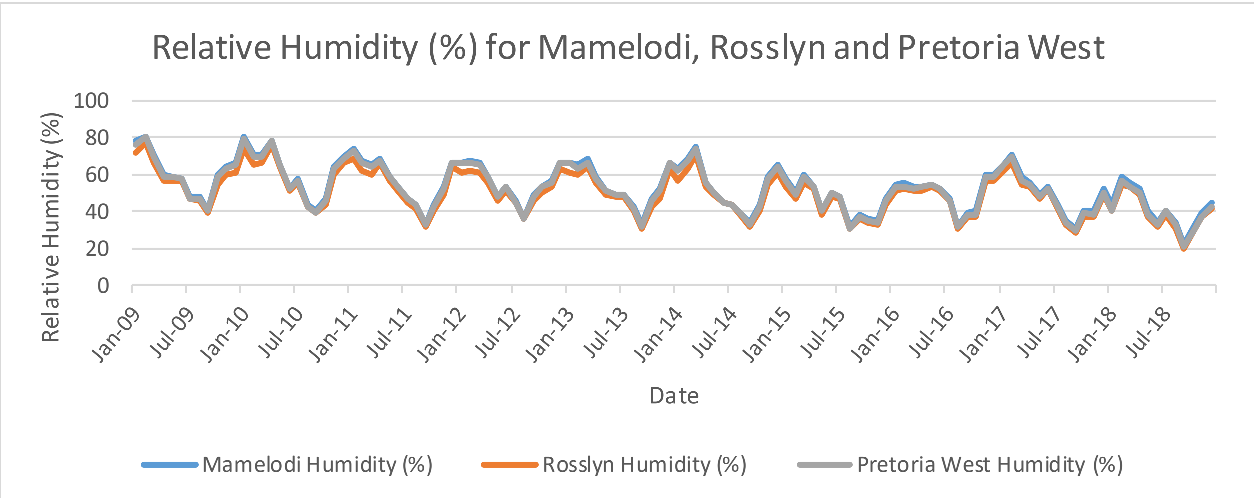



**Figure 5. 6: Temporal variation of relative humidity for the three stations over the period 2009-2018**

On average, January and February are the most humid months in the three sites in Gauteng (79-81 %), and August is the least humid month (dry but windy winter month in Gauteng). The average annual percentage of humidity is 62.0 % in these three areas. Humidity in summer implies that chemical reactions requiring water vapour are accomplished more efficiently and hence airborne.

The summer season in Gauteng is associated with high humidity, which decreases harmful $PM_{10}$ in the air. The winter seasons are characterised by low humidity and high $PM_{10}$

concentrations and the prevalence of increased respiratory illnesses and conditions such as asthma and bronchitis, which thrive in low humidity environments and cold winter temperatures.

### 5.3.4 Importance of meteorological variables in the City of Tshwane

Meteorological variables are vital in determining the concentration and impact of the sources on the surrounding environment, and the relationship between the $PM_{10}$ concentrations and the wind speed and direction are considered. The periods of highest $PM_{10}$ concentrations relate to periods of high wind speed, typically greater than 6m/s. These are the periods when the high $PM_{10}$ concentrations are likely to be attributable to the generation of windblown dust. Marticorena and Bergametti (1995) modelled the age of aeolian dust dependent on limited friction velocities, or the point at which the wind speed is sufficiently high to enter soil particles from the surface. This approach has effectively been utilised to represent dust generation in various regions (Kocha et al., 2011; Schmechtig et al., 2011).

The findings of this work demonstrate that the study area population remains exposed to and thus endangered by their continuous exposure to $PM_{10}$. The generation of this dangerous pollutant results in part from economic activities that also support the livelihood of the communities. However, such factories and power-generation facilities will have to adhere to the regulations and standards set by the applicable laws to ensure human wellbeing.

This study concludes the findings and recognises the following framework to mitigate the emission of $PM_{10}$ on a local community basis:

- Economic activities are vital; however, stricter regulations and ongoing monitoring need to be implemented, supported by suppression technology to mitigate the generation of $PM_{10}$.
- An affordable alternative should be available for low-income households and informal settlements to eliminate their need to burn coal/biomass, which contributes significantly to dangerous emissions, damaging their health.

During the winter months, a high pollution level is visible in those areas where smog engulfs these residential areas.

Some $PM_{10}$ may contain heavy metals, silica, bacteria, pollen, asbestos and other toxic industrial by-products. Simple engineering technologies should be put in place to suppress the emission of these by-products. The following suggestions may be cost-effective for industries and activities that emit $PM_{10}$:

Used industrial water may be recycled or re-used as a $PM_{10}$ suppression technology, reducing the need to use expensive fresh or drinking water and thus not compromising the water supply.

Using dust-retardent products such as liquids that bond or dry dust particles on dusty roads and dust-generating industries might significantly reduce $PM_{10}$ emissions.

Agricultural activities also generate $PM_{10}$. Mulching of the land not only prevents excessive evaporation of the much-needed water, but also reduces dust emission to the environment.

# CHAPTER 6: SUMMARY

The primary aim of this research was to evaluate air quality, with a focus on the major air pollutants in the City of Tshwane, Gauteng. The study focused on the concentrations of $PM_{10}$ and $SO_2$ at three continuous air quality monitoring stations at various areas in the City of Tshwane. Meteorological parameters were assessed, and monthly and seasonal variation was used to identify the impacts caused by these pollutants and how the concentrations of the contaminants influence the environment and human health. Based on the findings, two key ambient air pollutants, $SO_2$ and $PM_{10}$ concentrations in sampled areas in the City of Tshwane, were found to be generally high during the winter months (with frequent inversions) and lower during the summer months (effects caused by the absence of vertical mixing). It can be concluded that anthropogenic activities in the city are key contributors of $PM_{10}$ and $SO_2$, with high levels more enhanced by meteorological/weather conditions in residential areas. The results demonstrate that due to biomass burning and coal-powered power plants, poor air quality is concentrated in a few regions of the city, particularly in low-cost residential and industrial sectors.

Meteorological factors play a vital role in the observations of this study. High levels of humidity and rain were found to be some of the meteorological parameters that influence the daily concentrations of $SO_2$ and $PM_{10}$ in the areas (humid and rainy days tend to exhibit lower concentrations of the analysed pollutants). While an increase in temperature can cause a decrease in pollutants in the atmosphere, it can also cause resilient turbulent currents and precipitation that dilutes the concentration of pollutants emitted at the Earth's surface.

It is vital to highlight the importance of considering meteorological parameters (wind direction and speed, rain, humidity and temperature) on $SO_2$ and $PM_{10}$ concentrations. Monthly and seasonal variation is also crucial in observing seasonal changes due to pollutant concentrations and thus coming up with solutions to mitigate or minimize massive air pollution emissions. Future developments in air pollution standards must consider the impact of specific meteorological parameters on individual pollutants and the establishment of more stringent winter air pollution standards, particularly in industrialised areas.

# CHAPTER 7: RECOMMENDATIONS FOR FUTURE PERSPECTIVE

## 7.1 Recommendations to limit $SO_2$

- Recommendations for future action should be considered, and standards should be reviewed every five years or even more frequently to identify any new data on the effects of pollutants on human health and the environment and the implications of any long-term changes caused by pollution.

- Low-income homes and informal settlements contribute significantly to the ambient air pollution caused by gases such as sulphur dioxide and particulate matter. Thus, while the residents endanger their health, they also threaten others living or working in those environments and contribute negatively to climate change. Looking towards the example of China, South Africa needs to move away from coal-burning power plants as they prove to be the most significant contributors to air pollution and establish alternative energy resources that are also affordable by the poor and are not detrimental to a human's health.

- Because measurements of sulphur oxides and total suspended particles are primarily used as markers of the pollution mix in the ambient air, in addition to continuing to eliminate these pollutants, efforts should also be undertaken to regulate other contaminants that are a risk to the environment and human health.

- Because the majority of the information of impacts described in this study is based on sulphur oxides and smoke in combination, these pollutants are not entirely indicative of contemporary pollution exposure in a number of communities. Epidemiological studies are needed to determine the potential consequences of other forms of particle pollutants, such as sulphuric acid and sulphates.

- It is recommended that existing monitoring practices be reviewed and, if necessary, appropriately enhanced as a result of the conclusions reached on the harmful effects of sulphur oxides, smoke, and all suspended particulates on human health, as well as the related guidelines for the protection of public health. The World Health Organization should undertake consultations with environmental scientists, inhalation toxicologists, and epidemiologists to consider both the epidemiological and control aspects of the problem to assist regulatory agencies in this respect,

- There is a scarcity of data on occupational exposure that may be used in exposure-effect analyses. As a result, such investigations are advised, particularly in the case of sulphur dioxide and associated contaminants. These investigations should incorporate pollution measurements over entire working shifts, taking into account fluctuations in space and time during shorter time periods and including exclusionary criteria.

### 7.2 Recommendations to limit $PM_{10}$ level

Future research in this area should look at exposure assessment, and furthermore:

- Examine a wide range of $PM_{10}$ sources, including local and regional wood-burning and desert dust, in addition to road traffic and heating and electricity generation.
- Take into account the different emission sources' contributions to the population's exposure;
- In long-term studies, take into account possible changes in exposure parameters (level, $PM_{10}$ composition, co-pollutants) over time (for example, include evaluation).
- In studies of $PM_{10}$ that are connected to human health and the environment include the assessment of additional pollutants, namely nitrogen oxides (NOx).
- When possible, increase the spatial resolution of exposure estimations to account for smaller-scale differences in space; and
- Improve individual exposure estimates to eliminate the need for epidemiological investigations to rely on data from stationary monitors.
- To improve exposure modelling and more precisely attribute pollution exposure to pollution sources, gaps in pollutant emission information and research must be closed.

- Improved air quality monitoring should improve exposure assessment and enable low-cost, easy-to-use $PM_{10}$ monitoring tools, particularly for predicting long-term exposures.
- In addition, the relationship between $PM_{10}$ and meteorological parameters should be examined further for both industrial and residential sites in order to better understand air dispersion phenomena and seasonal change. More research is needed to better understand $PM_{10}$ concentration trends in South Africa, as well as to strengthen air pollution controls and build a warning system.

## 7.3 Future perspectives

There are a number of knowledge gaps in studies around ambient air pollution that follow from our findings and would benefit from the future investigation. The following should be ensured in future research:

- Using back trajectory models, researchers can link acute health outcomes to specific pollution sources, providing for a better understanding of the detrimental health repercussions of high-pollution episodes. Validation of dispersion models used by epidemiological studies and risk assessment procedures;
- Identification of the contribution of primary and secondary $PM_{10}$ components to the total PM mass and explore the role of various characteristics of superfine, fine and coarse particles responsible for harmful health effects.
- The level of $SO_2$ is not only affected by emission sources but also by weather conditions, which should be investigated further in future studies.
- Future research should ensure that air-monitoring stations are closely monitored and frequently serviced to ensure that they are adequately operational at all times to avoid gaps in data.

# 8. Appendix

## 8.1 Mamelodi

**Figure 8.1: Mamelodi Summary Plot**

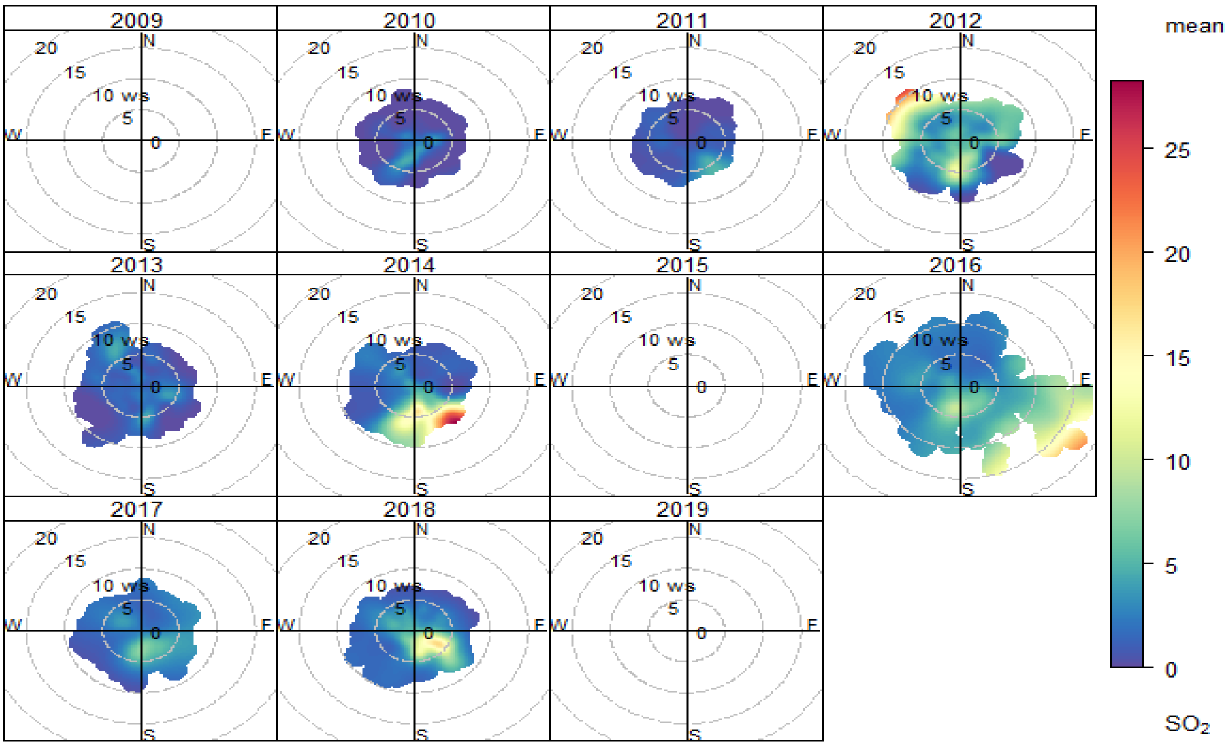


**Figure 8.2: 2009-2019 Polar Plot $SO_2$**

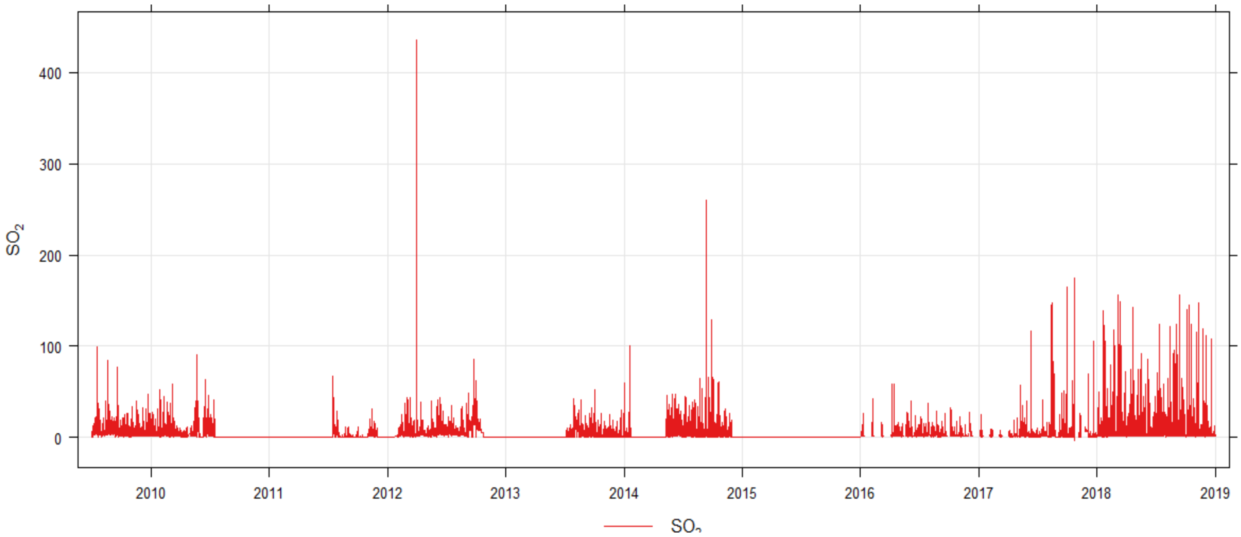



**Figure 8.3: Mamelodi $SO_2$ Time Plot**

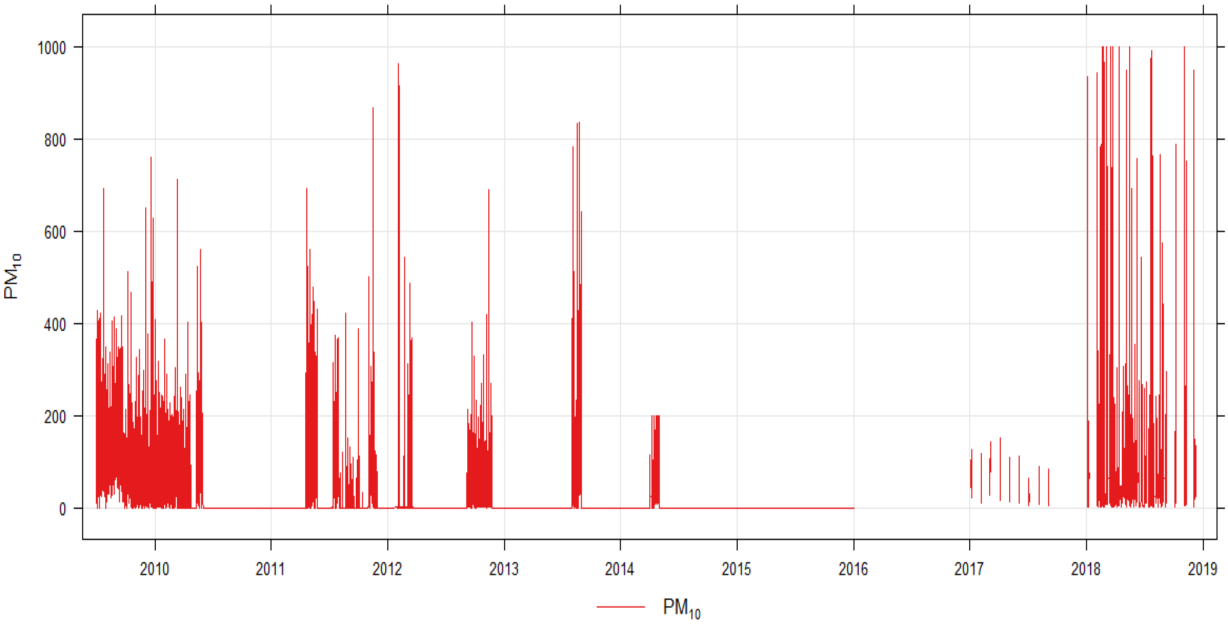



**Figure 8.4: Mamelodi $PM_{10}$ Time Plot**

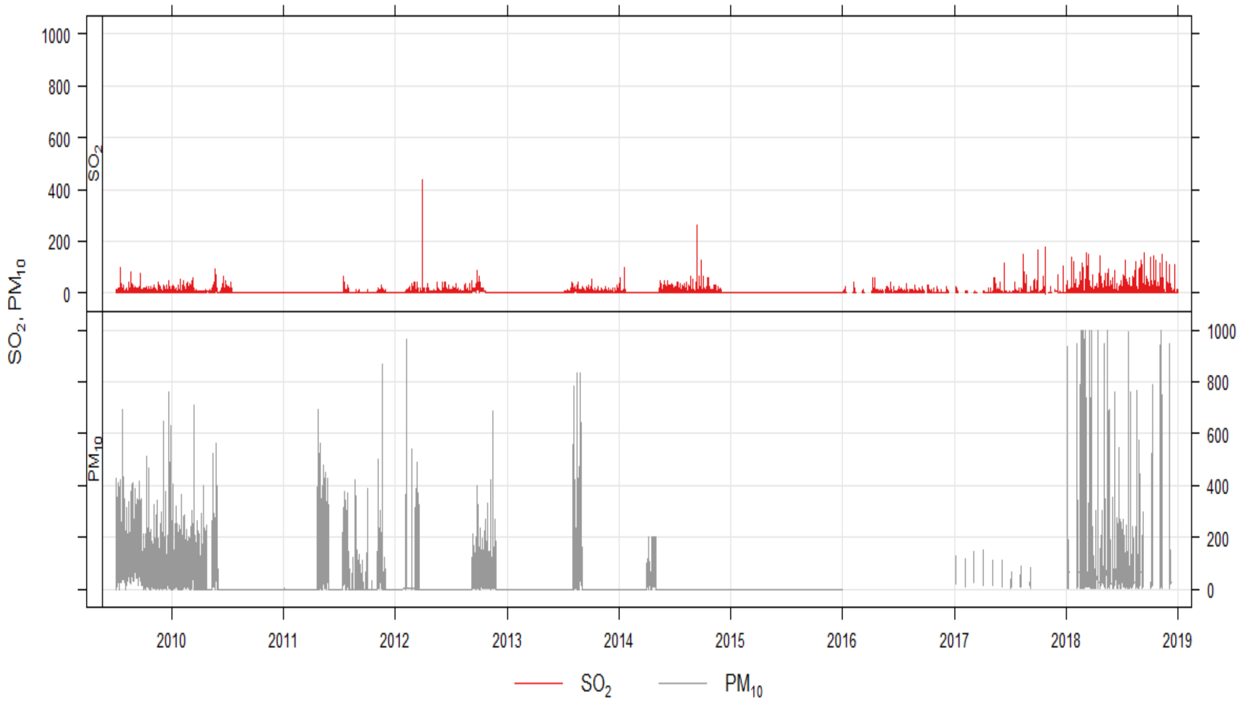



**Figure 8.5: Mamelodi $SO_2$ and $PM_{10}$ Time plot**

## 8.2 Pretoria West

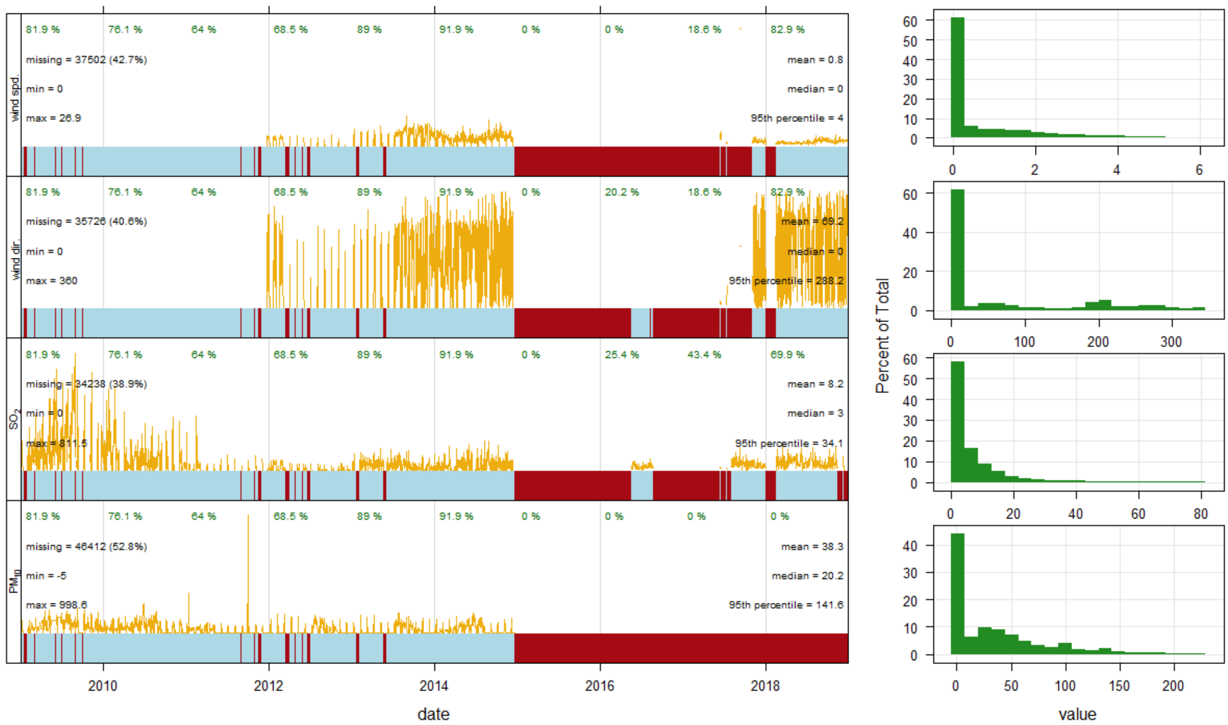



**Figure 8.6: Pretoria West Summary Plot**

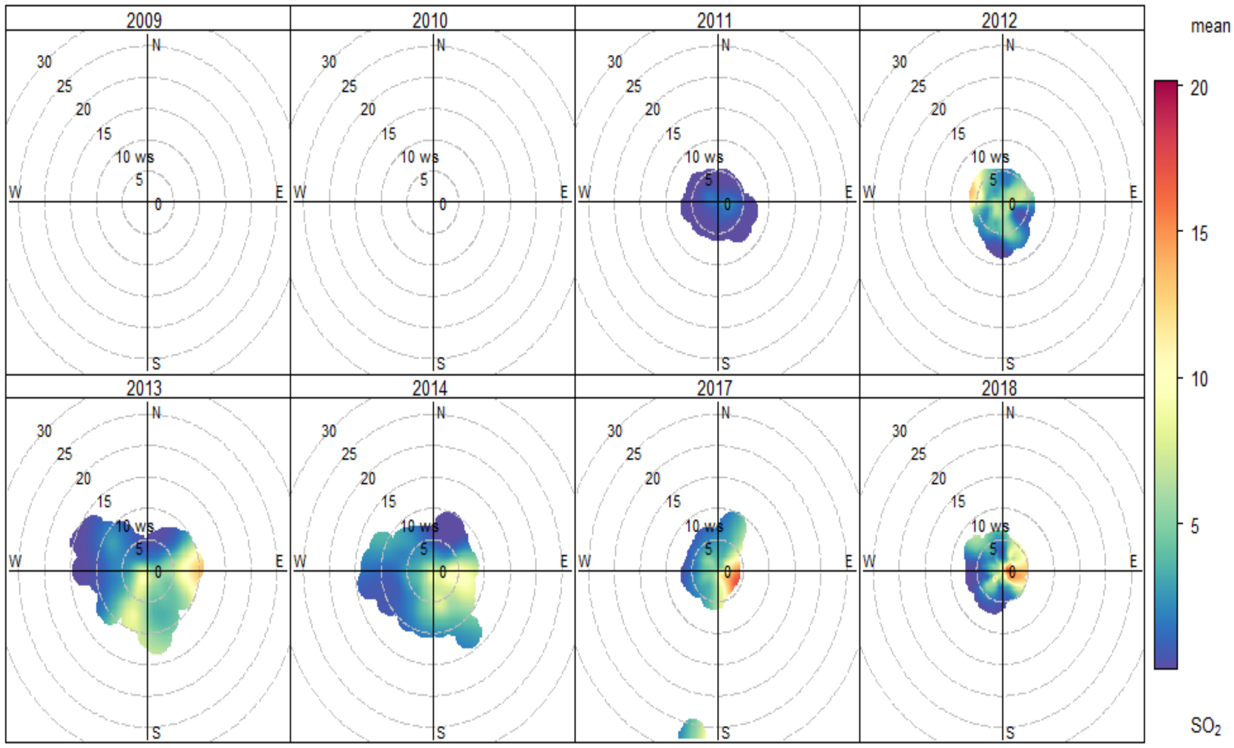



**Figure 8.7: Pretoria West 2009-2018 $SO_2$ Polar Plot**

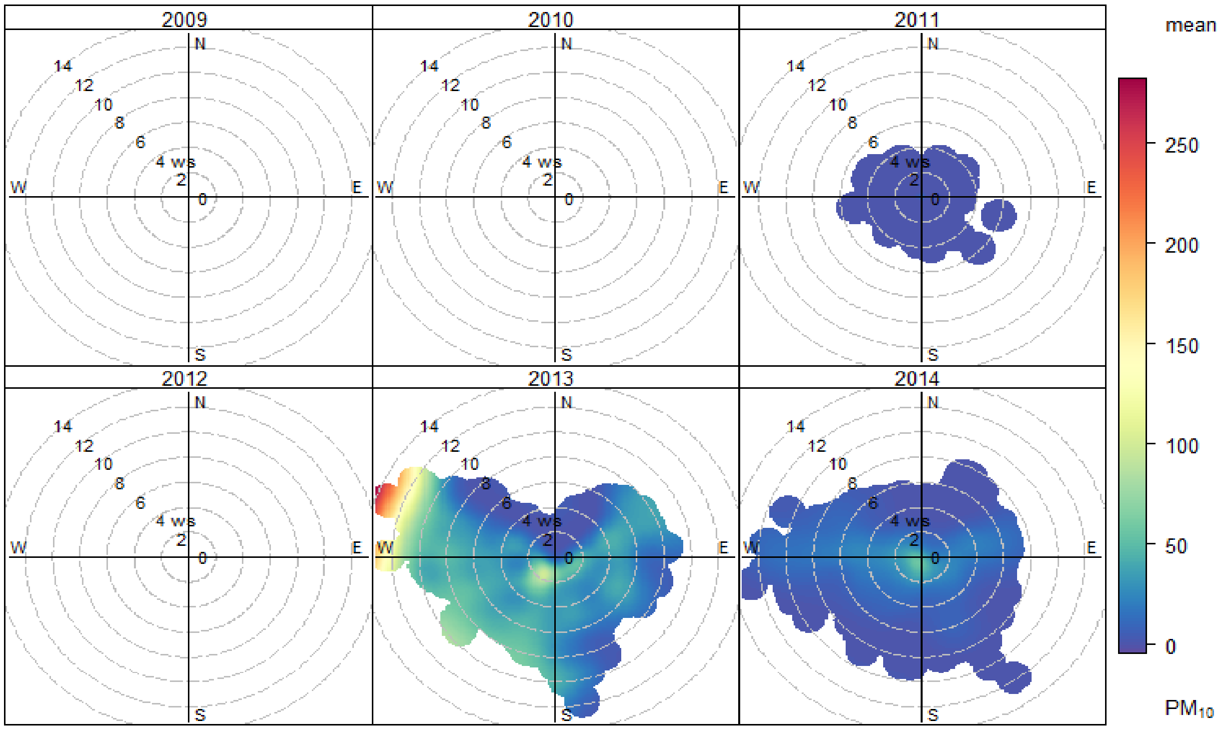



**Figure 8.8: Pretoria West 2009-2014 $PM_{10}$ Polar Plot**

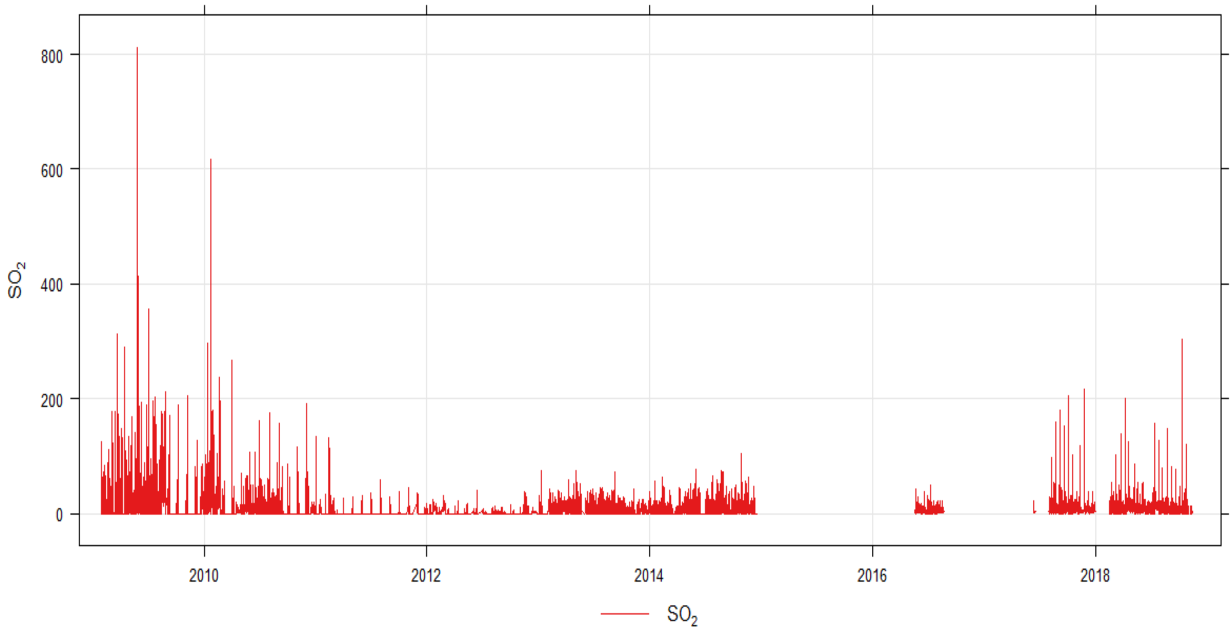



**Figure 8.9: Pretoria West $SO_2$ Time Plot**

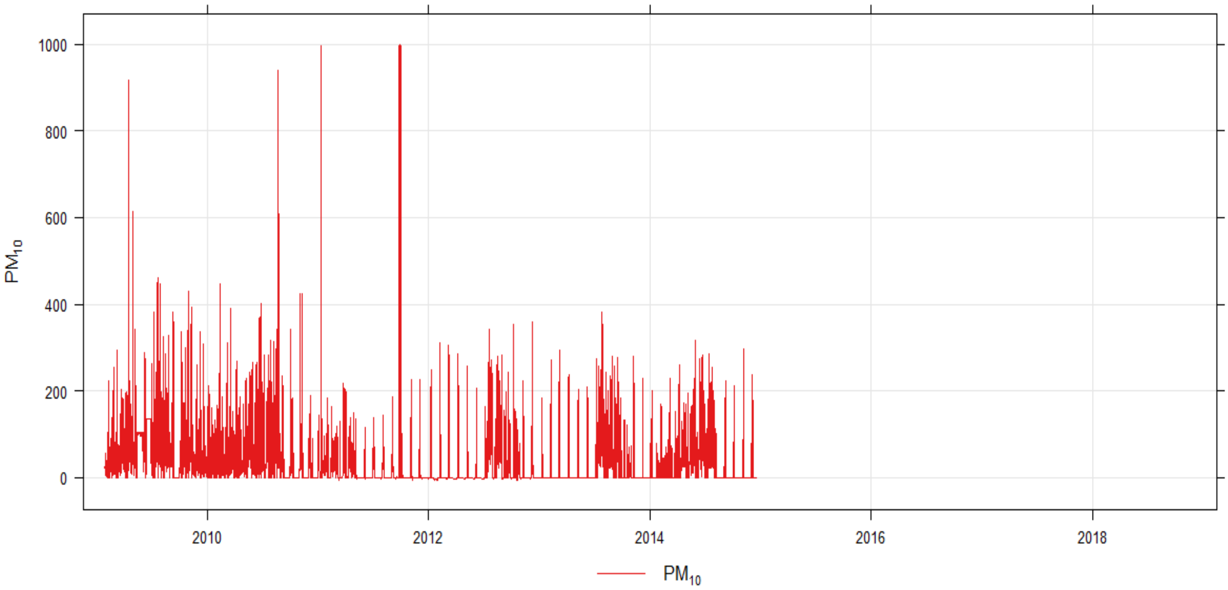



**Figure 8.10: Pretoria West $PM_{10}$ Time Plot**

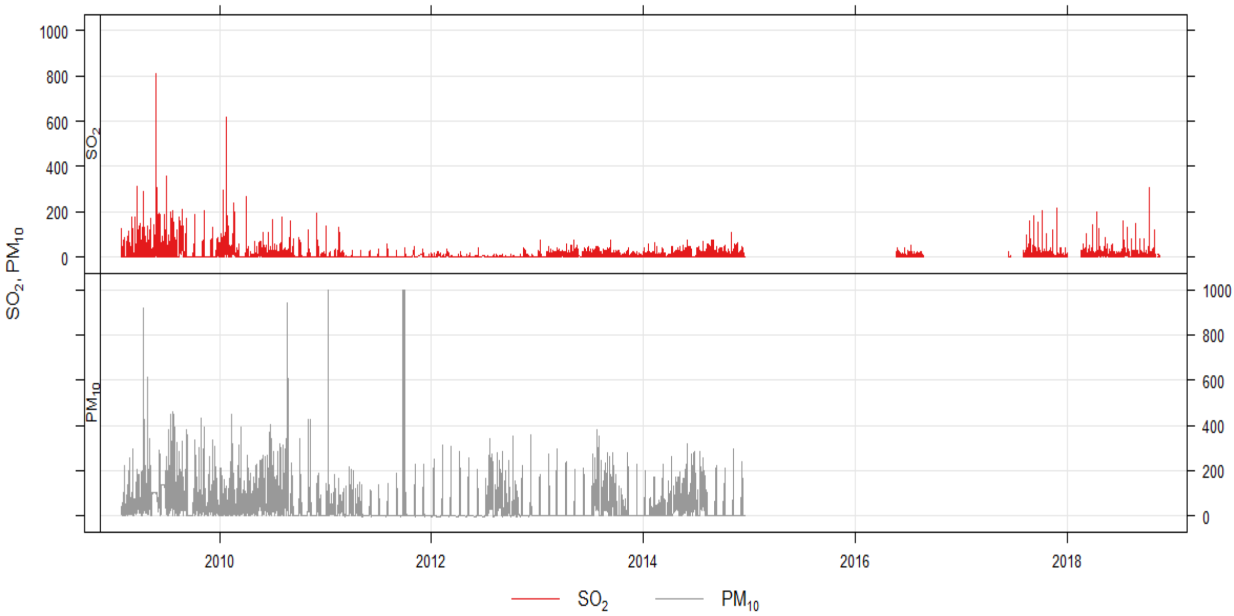



**Figure 8.11: Pretoria West $SO_2$ and $PM_{10}$ Time Plot**

## 8.3 Rosslyn

**Figure 8.12: Rosslyn Summary Plot**

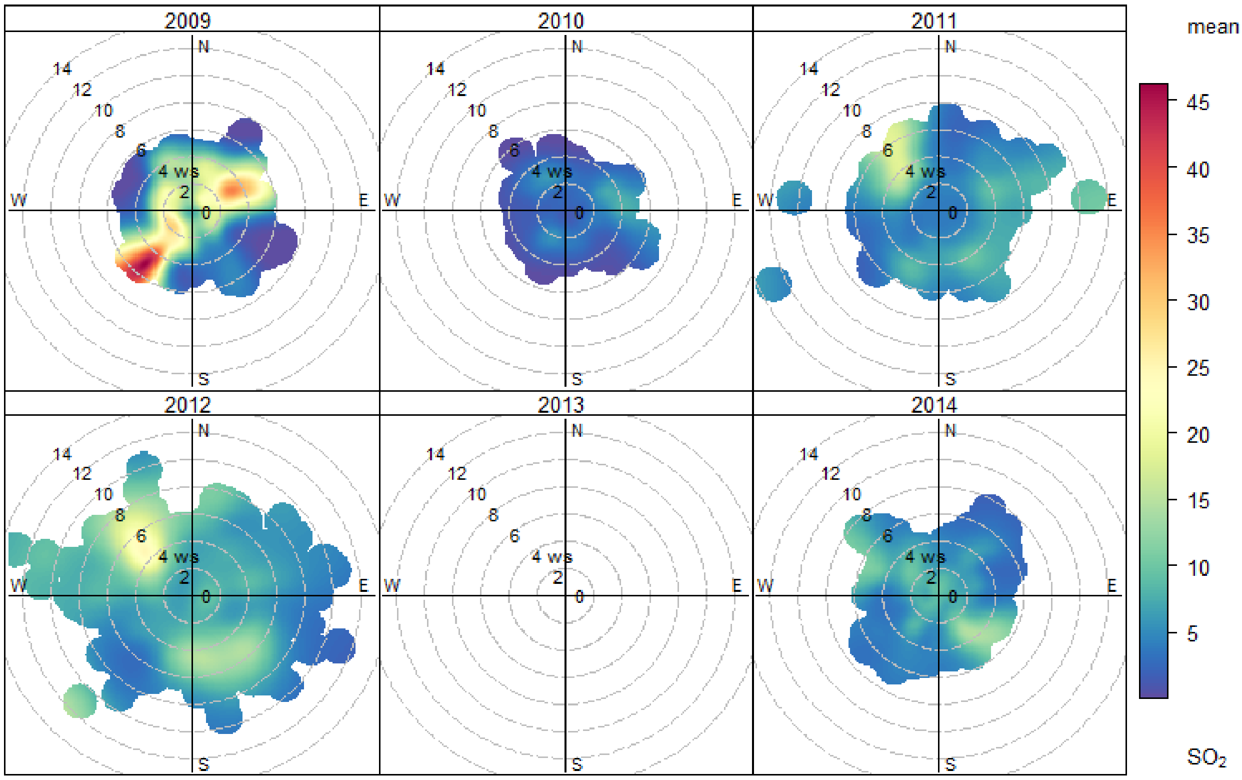


**Figure 8.13: Rosslyn 2009-2014 $SO_2$ Polar Plot**

## Rosslyn

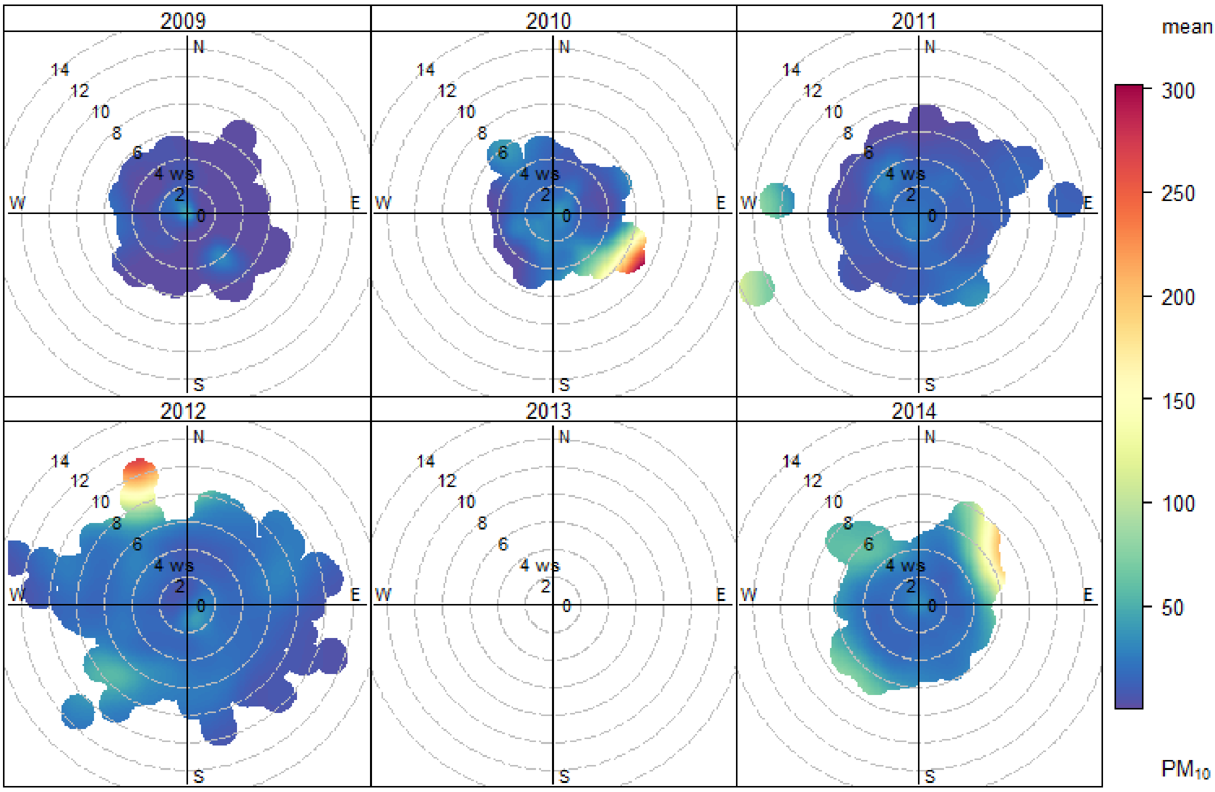



**Figure 8. 14: Rosslyn 2009-2014 $PM_{10}$ Polar Plot**

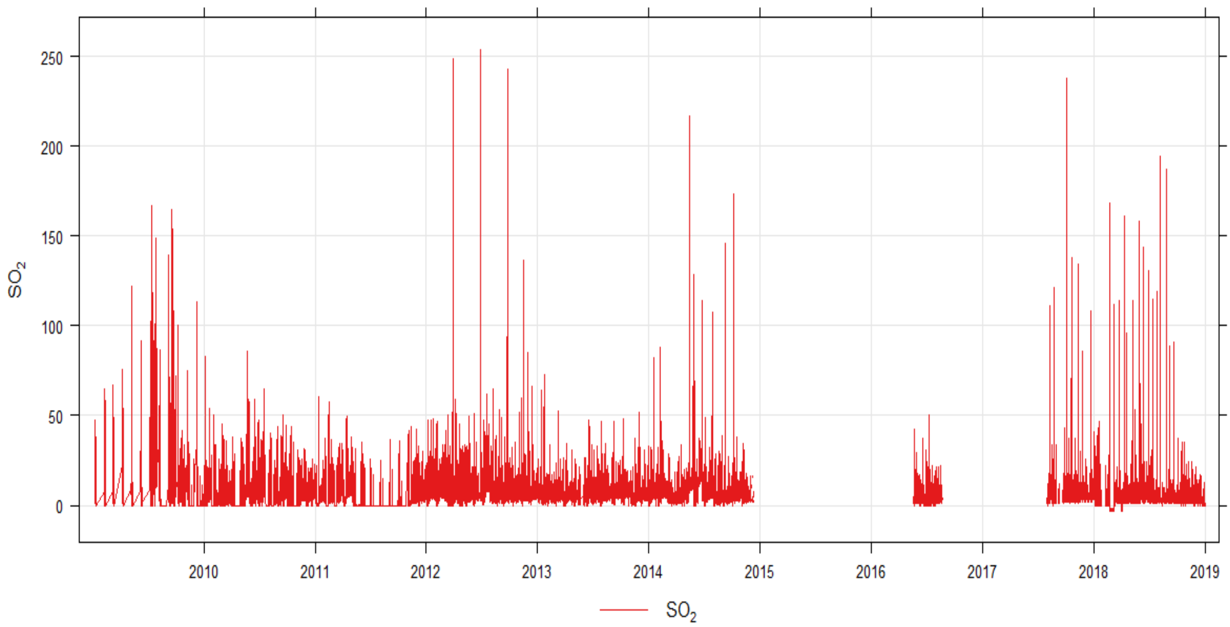



**Figure 8. 15: Rosslyn $SO_2$ Time plot**

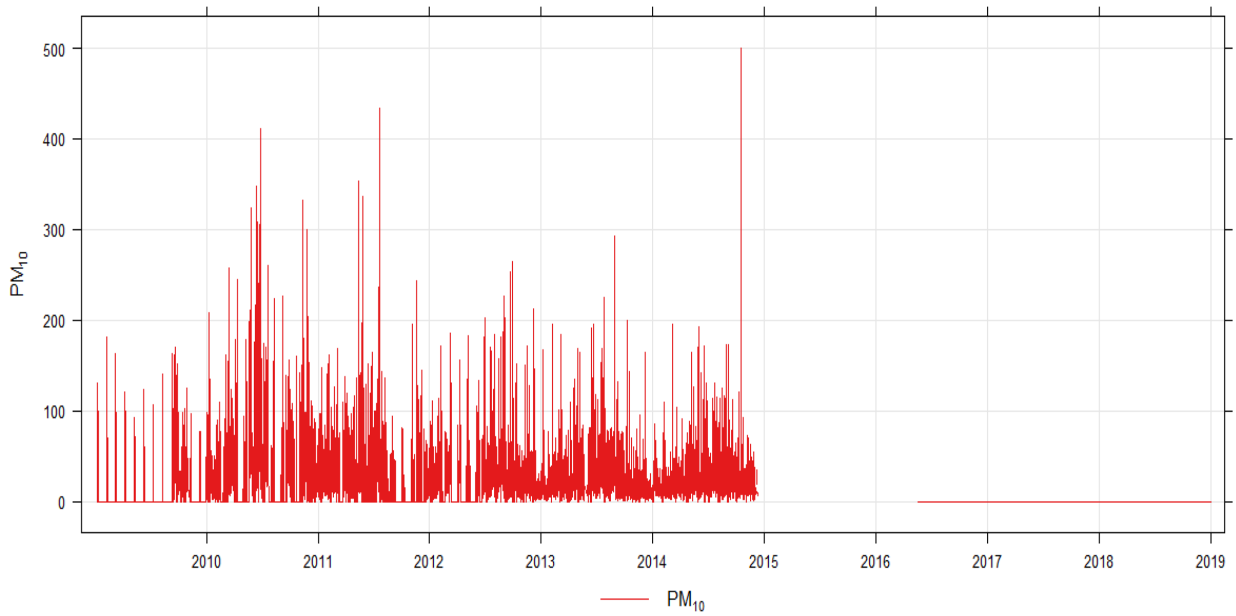



**Figure 8.16: Rosslyn $PM_{10}$ Time plot**

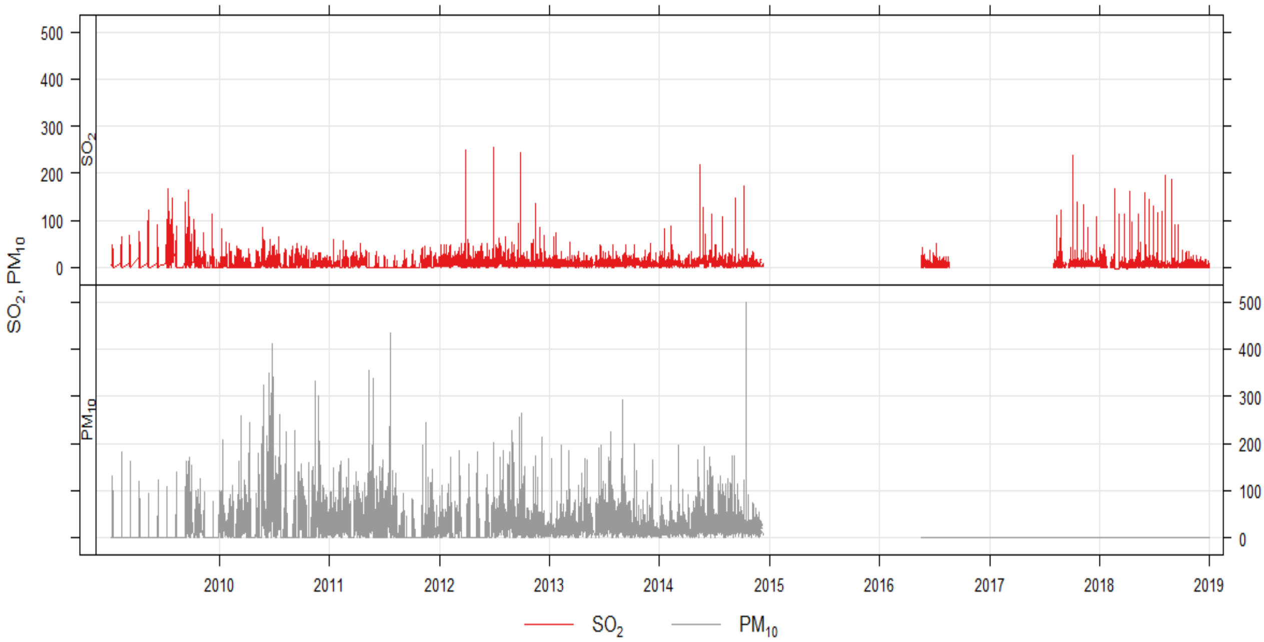



**Figure 8.17: Rosslyn $SO_2$ and $PM_{10}$ Time Plot**

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