SPATIAL DISTRIBUTION OF AMBIENT AIR QUALITY IN THE CAPE TOWN CENTRAL BUSINESS DISTRICT

By

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DECLARATION

I, **Ongeziwe Ndletyana**, declare that the contents of this dissertation/thesis represent my own unaided work and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

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Signature Date

PREFACE

Some extracts of this thesis have been accepted in a peer-reviewed international journal accredited by Department of Highre Education and Training:

1**.Ongeziwe Ndletyana**, Benett Siyabonga Madonsela and Thabang Maphanga. Spatial distribution of PM_{10} and NO_2 ambient air quality in Cape Town CBD, South Africa. Nature Environment and Pollution Technology. (Paper No. D-1412) in press.

ABSTRACT

The scourge of ambient air pollution exposure has been described as a public health threat facing the 21st century generation. Majority of countries worldwide are exposed to high levels of air pollution exceeding the prescribed exposure limits. In developing countries, exposure assessment of air pollution is a constant challenge even though air pollution is a public health risk. Literature indicates that in developing countries ambient air pollution is generally monitored using fixed air quality monitoring stations. This practice is associated with the limitations to capture the spatial variability of air pollutants. The aim of this study was to map the spatial distribution of ambient air quality in Cape Town CBD using Geographic Information System (GIS).

The study used ambient air quality secondary data (raw data) retrieved from City of Cape Town (CoCT) Air Quality Monitoring (AQM) stations for particulate matter and nitrogen dioxide. There are two monitoring stations located at Cape Town CBD which are Foreshore AQM and City Hall AQM. Each station is designed to collect data on a particular pollutant. For instance, the Foreshore AQM station is designated to measure PM pollutants whilst the City Hall AQM station measures the NO_2 pollutants. Moreover, these stations collected data intermittently, as a result, the current data obtained from the CoCT municipality mostly covered the years of 2017 to 2018. The results of this research were presented and analysed using ArcGIS 10.8 pro a product of ESRI. Heat maps were produced using the mean concentration of geostatistical analysis called the Inverse Distance Weighted (IDW) interpolation method. The graphs and tables were produced using a Microsoft Excel spreadsheet.

The findings of the study show a distinct spatial variation that PM_{10} was the main pollutant in the CBD with a high concentration between summer and winter within the years of 2017 and 2018 while NO_2 pollutant was lighter. The study further indicated that meteorological conditions such as wind speed and temperature could have a correlation close with the ambient air pollutants and play an important role in the spatial distribution of PM_{10} and NO_2. Although the meteorological factors are not studied in this study, the findings were comparable with others studies conducted globally. Moreover, the national traffic roads entering the CBD, industrial harbour and dense residential areas with high buildings were considered in ascertaining as the pollution hotspot in the CBD.

The study recommends the use of meteorological data to study the spatial distribution variability in a region as it has an important role in the distribution of ambient air pollutants. It was also noted that the fieldwork should be carried out because it would provide primary data and a lot of details compared to relying on secondary data.

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In addition, I would also like to thank the City of Cape Town Municipality; City Health Department for making time in the busy schedule and granting me the permission to use the air quality monitoring station data and making sure that I have access information for my research.

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Thank you to my close friends for their support, thoughts and patience while I was doing this thesis.

The financial assistance of the **CPUT POSTGRADUATE BURSARY** towards this research is acknowledged. Opinions expressed in this thesis and the conclusions arrived at, are those of the author, and are not necessarily to be attributed to **CPUT POSTGRADUATE BURSARY.**

DEDICATION

I would like to dedicate this thesis to the angel that have departed from this earth; Lumkile Mdunyelwa for being the best father figure in my life, for instilling the passion of learning, teaching me to be disciplined at all times, and making me to understand the value of life. This thesis goes to you for the role you have played in my life into shaping the person I am today.

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ABBREVIATIONS AND ACRONYMS

$\mu g/m^3$: micrograms per cubic meter

AQI: Air Quality Index

AQM: Air Quality Monitoring

CBD: Central Business District

CoCT: City of Cape Town

GIS: Geographical Information System

GPS: Global Positioning System

IDW: Inverse Distance Weighted

NEMAQA: National Environmental Management Air Quality Act

NO_2: Nitrogen Dioxide

PM_{10}: Particulate Matter aerodynamic diameter equal to or less than 10µm

$PM_{2.5}$: Particulate Matter aerodynamic diameter equal to or less than 2.5µm

SAAQIS: South African Air Quality Information System

CLARIFICATION OF BASIC TERMS AND CONCEPTS

Air pollution: is centred around the concept of direct and indirect introduction of substances into the atmosphere that has adverse effects on the environment and human health (Shezi and Wright, 2018).

Air Quality Monitoring: is the systematic, long-term assessment of air pollutant levels by measuring and monitoring the quantity and type of certain pollutants in the environment such as residential, industrial, commercial as well the roadside areas (US EPA, 2019).

Ambient Air: is the air that is found in the environment excluding the air that is found indoors (DEADP, 2017).

Geographic Information System: is an important tool for scientific researchers in terms of data processing, analysing geographical distribution, mapping, monitoring and management of health pandemics (Longley, 2005).

Hazardous delineated zone: is any areas that have high concentration exposure levels of air pollutants which can cause adverse effects to human health and/or environment (Adedeji et al., 2016).

Inverse Distance Weighted: is the method used to determine the air pollution status in areas that are not covered by the fixed monitoring station (Ibrahim et al., 2012).

Nitrogen Dioxide: is a highly reactive oxide of nitrogen which is brownish in colour (Kaos, 2010).

Non-hazardous delineated zone: is an area where air quality concentration exposure is considered satisfactory, and air pollution poses little or no risk to human health and/or environment (Law Insider, 2021).

Particulate Matter: is the mixture of solid particles and liquid droplets in the air which vary in terms of season and region (WHO, 2013; Yang et al., 2018)

Spatial Interpolation: is the method used to estimate the value of the variables under study at unexplored areas using point observations within the same region (Kumar et al., 2015).

Fixed Monitoring Station: are stationary equipment that consist of mobile units containing instruments to measure certain air pollutants (DEADP, 2018).

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND TO THE STUDY

Air pollution is centred around the concept of direct and indirect introduction of substances into the atmosphere that has adverse effects on the environment and human health (Shezi and Wright, 2018). Air pollution is mainly caused by several sources that discharge large quantities of gaseous mixture and particulate concentrations into the air these sources could either be natural and/or anthropogenic (Amaral et al., 2015). The sources of air pollution are distinguished either as primary or secondary pollutants. Primary air pollutants (such as particulate matter, oxides of nitrogen and sulphur dioxide) are directly emitted into the atmosphere. Whilst secondary air pollutants (such as ozone and nitric acid) are formed as a result of the reaction of primary air pollutants in the form of photochemical oxidation and hydrolysis (Ibrahim et al., 2012). Major sources of primary pollutants are predominantly from the combustion of fossil fuels, mining, industrial activities, vehicular-traffic and as a result of domestic space heating. According to Shezi and Wright (2018), these pollutants pose a significant impact on air quality.

Moreover, due to the complex nature of these pollutants, their elevated exposure levels in the ambient air of cities and urban areas are associated with brown haze. According to Walton (2005), brown haze is the smog that is present in the air due to the accumulation of gaseous and particulate pollutants such as Particulate Matter (PM) and Nitrogen dioxide NO_2. Furthermore, it has been discovered that PM and NO_2 pollutants from vehicular traffic emissions are major sources of pollution in cities (Jackson, 2005). Gordon et al. (2004), lament the pollution of air quality in cities of developing countries. Recent studies share similar sentiments. A study for instance conducted in Tanzania by Jackson (2005), linked vehicular traffic emission with exposure to air pollution that consequently causes the formation of brown haze in cities. Likewise, in South Africa, Shezi and Wright (2018), noted that the high rate of personal vehicle use causes an increase in ambient air pollution exposure. The scourge of ambient air pollution exposure has been described as a public health threat facing the 21st century generation (IFEH, 2017). Cities and urban areas are confronted with this scourge. WHO (2016), corroborate that countries worldwide are exposed to high levels of air pollution exceeding the prescribed exposure limits. Szyszkowicz et al. (2008), stress that pollution of the air is significantly associated with high risks of morbidity and mortality. South Africa alone records a total number of 14 356 confirmed cases of mortality associated with air pollution-related illnesses on an annual basis (WHO, 2016).

Globally, epidemiological studies indicate that about seven billion deaths are associated with ambient air pollution exposure (Mannucci and Franchin, 2017). In Africa, the effects of air pollution exceed that of malnutrition and polluted water (Roy, 2016). Thus, the adverse effects associated with exposure to ambient air pollution necessitate exposure measurement and reporting of air quality (Ibrahim et al., 2012). These adverse effects affect both developing and well-developed countries. However, there is a notable difference in the management of exposure to ambient air pollution between these countries. Developed countries, for instance, prioritize exposure measurement and improvement of ambient air quality. Whereas on the contrary, in developing countries the exposure assessment and subsequent management are neglected in the interest of economic development; despite several scholars highlighting the importance of ambient air quality exposure assessment and how its influencing factors can be advantageous to the benefit of the public health and well-being (Matooane et al., 2004; Venter et al., 2012; Dong et al., 2020).

Recently Coker and Kizito (2018), acknowledged that SA is the only region with improved ambient air quality monitoring systems in Southern Africa. This is due to the fact that in SA the spheres of government are entrusted with exposure assessment of ambient air pollutants (DEADP, 2017). Therefore, to fulfil this mandate, the spheres of government have erected automated fixed air quality monitoring stations across the country (Gwaze and Mashele, 2018). However, gaps and shortcomings have been associated with this practice.

1.2 STUDY AREA

Cape Town is one of SA's capital cities which falls under the legislative capital. it is normally referred to as the Mother City. Cape Town is the largest city located on the western cape, situated southwest coast beneath the imposing Table Mountain with GPS coordinates -33º55'29.64" S and 18º25'26.75" E. The city occupies an area of about 2 461km^2 and with an average elevation of 1 590.4m above sea level. It is bordered by the Table Mountain range along the west coast which influences airflow within the region. The Cape Town climate is the Mediterranean, with warm, dry summers and mild, moist winters. It has a wind force called "Cape doctor", which helps to blow away smog and impurities to clear the skies and make a way for some fresh air (World Weather and Climate Information, 2019).

According to Census (2011), the Cape Town population is about 3 740 026. Increased urbanization and economic activities have resulted in many people in the area. This has consequently increased the number of potential users of public transport (taxis, buses, and trains); private transport included as well (Walton, 2005). According to CoCT (2002), the CBD experiences massive volumes of traffic congestion during peak hour periods i.e. in the morning and afternoon. Thus, Cape Town experiences high pollution levels from motor vehicle exhaust emissions, which is characterised as the major contributor to the formation of brown haze (Walton, 2005). The brown haze is noticeable from April to September due to strong temperature inversions and calm conditions that are experienced during this period. The haze extends over most of the City of Cape Town (CoCT) and shifts according to the prevailing wind direction (Wicking-Baird et al., 1997; Keen and Altier, 2016).

1.3 PROBLEM STATEMENT

The South African spheres of government are mandated to monitor ambient air quality exposure levels as prescribed by the National Environmental Management Air Quality Act (NEMAQA, 2004). To fulfil its mandate, the spheres of government have erected automated fixed air quality monitoring stations across the country. However, this practice is not without limitations. It is associated with a constant challenge of monitoring the spatial distribution of ambient air pollutants on a large scale. These include the inability to cover the wide spatial variability of air pollutants distribution on a larger scale. This translates to assumptions about air quality exposure levels of subjects positioned kilometres away from the fixed monitoring stations, especially within the urban areas. Literature indicates that limited information on the spatial distribution of air pollution is a challenge facing developing countries (Sajani et al., 2004; Coker and Kizito, 2018; Dias and Tchepel, 2018). It is evident therefore that there remains a need to comprehend the spatial distribution of air pollutants to effectively understand the risks of air quality on human health and wellbeing, especially within developing countries.

1.4 RESEARCH QUESTION

What is the spatial distribution of ambient air quality in the cape town central business district?

1.5 AIMS AND OBJECTIVES

The aim of the study is to map the spatial distribution of PM_{10} and NO_2 pollutants in Cape Town central business district

- To investigate and map the spatial distribution of PM_{10} and NO_2 in the CBD
- To determine the spatial behaviour of PM_{10} and NO_2 concentration in the CBD
- To assess the seasonal (summer and winter) distribution of PM and NO_2

1.6 RATIONALE AND/ SIGNIFICANCE OF THE STUDY

A growing number of scientists, especially in developed countries have experimented with the use of technologies such as GIS to help or assist in monitoring the spatial distribution of air pollution in big cities which yielded successful results (Harinath and Murthy, 2010). This was done to try and overcome the challenges associated with stationary monitoring systems which do not cover a wide range of the spectrum. Therefore, this study seeks to experiment with the use of GIS in monitoring air quality in developing countries using this technology (GIS). This study is significant as it will bring a new perspective on understanding the spatial distribution of ambient air pollution exposure. The introduction of this study will be crucial in determining the use of GIS software in mapping the spatial distribution of ambient air pollution. The greater the spatial detail provided can be advantageous in improving estimation based on interpolation between ground observation and dispersion models. Thus, GIS technology in air quality studies can be significant in human health exposure risk estimation, planning, quality assurance, and air pollution research (Xie et al., 2017).

1.7 EXPECTED OUTCOME

The expected outcome of this study includes being able to map the seasonal spatial distribution of ambient air pollutants (PM_{10} and NO_2) in the CBD using GIS; and model the spatial distribution of air quality. Mapping of pollutants distribution in the CBD using GIS is expected to cover a wide range of areas that under normal circumstances are not covered by the fixed monitoring stations. Mapping the spatial distribution of pollutants will be advantageous in estimating the risk of air pollution exposure, especially within areas in the CBD that are not regularly monitored due to the limitations of the exposure assessment associated with the fixed monitoring stations. The study will help a student to obtain a master's degree qualification.

CHAPTER TWO: LITERETURE REVIEW

2.1. INTRODUCTION

This chapter focuses on the literature review from the broader scope of the ambient air pollution which zoomed into Particulate Matter (PM) and Nitrogen Dioxide (NO_2). These pollutants are most relevant and widely used as indicators of traffic-related emissions, particularly in urban air quality. The increase of human population along with economic activities as well the growing vehicle fleet has increased levels of PM and NO_2 pollutants in cities (Atash, 2007; Gulia et al., 2015). Thus, it is crucial to monitor and measure these air pollutants because their concentration can be spatially distributed in urban areas, creating hot spots mostly in CBD as well in traffic intersections (Kandlikar, 2007).

Randle (2016) and Munir et al. (2019), assert that PM and NO_2 pollutants vary dramatically over a short distance and time intervals; thus, air quality measurements from fixed monitoring stations have not sufficiently specified the location of pollutants. Therefore, this study intends to investigate the common methods of assessing and monitoring the spatial distribution of PM and NO_2 within cities globally. In support of DEA (2012), it is significant to conduct air quality measurement and monitoring programs to determine air pollution in a region and to evaluate the effects on the environment and human health.

2.2. HISTORY OF AIR POLLUTION AND ITS EFFECTS

Ambient air pollution is not an emerging scourge that faces the 21st century generation, especially within cities and urban areas boundaries. The Archives record shows that the issue of air quality dates back to early seventies. It was recognized as a global issue in the 1970s even though historical prior studies of smog episodes were recorded in Donora and London (PA, 1948; UK 1952; US EPA (2017). In the early 1980s, researchers with the aid of science and technology sought to determine the link between air pollution exposure and subsequent risk factors (Gini, 2022). According to US EPA (2017), various studies have demonstrated that tiny particles discharged as a result of combusting fossil fuels i.e., coal have a subsequent impact on human health, resulting in a compromised respiratory and cardiovascular system. Sellier (2014), states that such impacts on human health have been less frequent in developed countries in contrast to developing countries where they have been observed and reported to be increasing at an alarming rate due to rapid industrialization and traffic congestion. An increase in these episodes is usually observed during the winter period.

Stern and Professor (1982), associate the industrial revolution with exacerbated air pollution emission sources. Likewise, Matooane et al. (2004); Keen and Altier (2016), discovered that population growth, widespread industrialization and urbanisation are responsible determinants for an increase in emission sources that generally accounts for poor air quality in the neighbourhood. In the early 1970s, these determinants were eventually linked with high concentration exposure levels of nitrogen dioxide and sulphur dioxide. Ultimately, they were recorded as the cause of acid rain which subsequently has adverse effects on the environment and human health (Mosley, 2014). According to Brimblecom (2011), it was the episode of acid rain in the 1970s that captured worldwide attention and sensitized the world about issues of air pollution and its subsequent effects.

Thus, in the 1970s states began passing legislation to reduce air pollution. Legislations are significant for effective air quality management; because they provide guidelines which assist to determine and indicate a difference between polluted and non-polluted atmospheres. Subsequently, evidence of air quality improvements emerged throughout the states (Gini, 2022). However, during the 1980s countries experienced a rapid increase in the number of motor vehicles in cities and/or urban areas which consequently caused more prevalent air quality problems again (Atash, 2007; Gulia et al., 2015). In the early 1980s, motor vehicles were once the major contributor to lead emissions which adversely impact human health; however, in the late 1980s, the effects of motor vehicles became a matter of concern (US EPA, 2021). Several scholars identified that recently the road transport sector is one of the major sources of air pollution which adversely cause problems to the environment and human health; particularly in CBD because of the ongoing and coming traffic congestion (Atash, 2007; Kandlikar, 2007; Núñez-Alonso et al., 2019). Thus, rapid urban population growth has increased the volume of motorized traffic which resulted in severe air pollution affecting the environment and human health (Gulia et al., 2015).

To protect the environment and human health Franchin and Mannucci (2015), suggested that ambient air pollution must be managed by regulating levels of exposure to acceptable. For this to be archived, the type of pollutant, level of exposure and factors influencing air pollution exposure must be identified and characterised (Matooane et al., 2004). Ultimately, developed countries invested their efforts and focus on monitoring and assessing the exposure of air pollution determining the subsequent impacts as industrialization kept evolving, and so was the source of air pollution. In developed countries, this prompted the evolution of monitoring systems which advanced to include the use of technology to effectively monitor exposure. However, to date, developing countries are struggling to effectively monitor exposure to air pollution.

2.3. INTRODUCING SOURCES AND CHARACTERIZATION OF PM AND NO_2

2.3.1. PARTICULATE MATTER AND NITROGEN DIOXIDE

Particulate Matter (PM) is the mixture of solid particles and liquid droplets discharged into the atmosphere as the result of the combustion of fossil fuels, power plants, domestic use for space heating and vehicle exhaust emissions (WHO, 2013; Yang et al., 2018). Due to mass and composition, in urban environment PM tend to be divided into two groups i.e., coarse particles and fine particles (Samara and Vousta, 2005). WHO (2013), describe PM groups according to size which is known as the width of the particles i.e., PM_{10} (coarse particle) and $PM_{2.5}$ (fine particles). Therefore, the suspended particles that are smaller than 10 micrometres (μm) in diameter (PM_{10}) are regarded as inhalable PM, whilst those that are smaller than 2.5μm $PM_{2.5}$ are known as respirable PM (Koas, 2010; Amaral et al., 2015).

It has been discovered that the size of PM particles affects human health differently thus the tendency to affect human health increases as the size of the particle decreases (Samara and Vousta, 2005; Koas, 2010). PM particles with a diameter greater than 10 μm have a relatively small suspension half-life and are largely filtered out by the nose and upper airway; whereas particles with a diameter between 2.5 and 10 μm can be lodged in the alveolus where health complications occur (Landsiedel et al., 2014; Yang et al., 2018). Hence, health complications associated with inhaling $PM_{2.5}$ include shortness of breath, coughing and wheezing, chest discomfort and pain as well as respiratory diseases and risks of developing lung cancer in the long term (WHO, 2013; Kim et al., 2015). These complications can either be classified as acute or chronic depending on their damage or reaction in human physiology.

In contrast, Nitrogen Dioxide (NO_2) is a highly reactive oxide of nitrogen which is brownish in colour (Koas, 2010) and it is a precursor to the formation of ozone pollution (Madonsela, 2019). It can exacerbate the formation of photochemical smog and has negative effects on human health. High exposure levels of NO_2 are associated with compromising human health. For instance, short-term exposure to NO_2 adversely cause airway responsiveness and lung malfunction due to injury, while long-term exposure may lead to respiratory infections (Gilbert et al., 2005). Epidemiological studies have shown that symptoms of bronchitis in asthmatic children increase in association with long-term exposure to NO_2 (WHO, 2018). According to Gilbert et al. (2005), sources of NO_2 can include mining activities and a significant portion from motor engines, which is a traffic-related pollutant.

2.3.2. SOURCES OF PM AND NO_2

Particulate Matter and Nitrogen dioxide can originate from a variety of direct and indirect sources i.e., factories and mobile sources thus may be emitted directly (primary emissions) or formed in the atmosphere (secondary emissions) by the transformation of gaseous emissions (WHO, 2013; Hasan et al., 2016). According to Kim et al. (2015), PM and NO_2 can be emitted from natural and/ or anthropogenic sources. However, scholars are adamant that a significant portion of PM and NO_2 emanate from a variety of anthropogenic activities (Hasan et al., 2016).

These include industrial processes, combustion of wood and fossil fuels, entrainment of road dust, and traffic-related emissions (Amaral et al. 2015; Hasan et al., 2016).

Interestingly of this traffic-related emissions account for a large amount of urban air pollution (van Vliet and Kinney, 2007; Kinney et al., 2011). Similarly, scholars like Keen and Altieri (2016), associate PM and NO_2 with traffic-related pollutants mostly emitted from motor engines. Hence, urban areas characterized by high-density road networks within proximity to residential areas are at risk of high exposure levels due to traffic-related exposure emissions. Correspondingly, Schwela (2012), has observed high trends of traffic-related pollutants in urban areas. Likewise, Singh et al. (2013), allude that traffic congestion is directly proportional to high exposure levels of PM and NO_2 within cities and urban neighbourhoods. Thus, it is important to note that, vehicular emissions became a major concern deteriorating the quality of air.

Figure 1: Below shows, the global distribution of sources and it is demonstrated that vehicular emission is the major contributor to air pollution followed by industrial activities. Several studies have observed that over 70% to 80% of air pollution in cities especially within developing countries is associated with vehicular emissions. This is mainly caused by many ageing vehicle fleets coupled with poor vehicle maintenance, inadequate road infrastructure and low fuel quality (van Vliet and Kinney, 2007). Thus, these causes are associated with emitting high levels of PM and NO_2 pollutants; for example, Johannesburg is recording the highest emissions that are associated with PM and NO_2 because of the concentrated city and several industrial activities (Lourens, 2011).

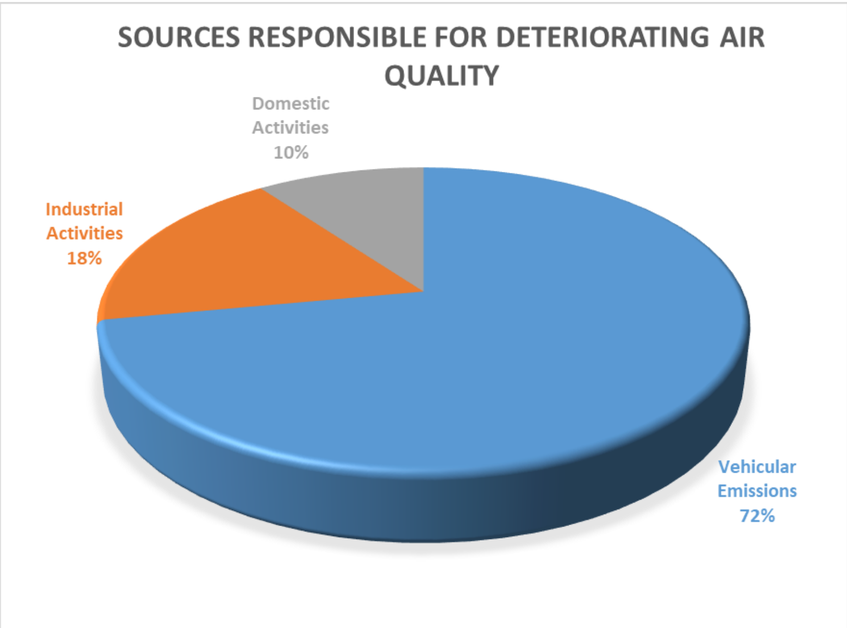

Figure 2.1: Sources responsible for deteriorating quality of air in the world (Kumar, 2015).

Additionally, Han and Naeher (2006), stated that NO_2 exposure in developing countries is usually higher compared to countries that are developed. Similarly, Kurtenbach (2012), observed that the increase of NO_2 in developing nations is mainly caused by the increasing number of motor vehicle exhaust, poor maintenance of many of these vehicles, narrow streets in the city as well several mining activities. For example, South Africa (Mpumalanga) is identified as the hotspot of air pollution with high concentration levels of NO_2, because of several mining activities which are taking place coupled with narrow streets in the city (Kekana, 2018).

2.4. AIR QUALITY MONITORING

Monitoring ambient air quality is the ongoing collection and analysis of data to determine compliance with legislation or policies (Völgyesi, 2008; Hedgecock et al., 2010). DEA (2012) and WHO (2013), believe that monitoring air quality exposure is more than just a data collection exercise; it is also about meeting legislative requirements in terms of providing information that policymakers, planners, and scientists need to make informed decisions about managing and improving the environment. Therefore, monitoring air quality is important to help in assessing the air pollution exposure to the environment and human health. Ortolani and Vitale (2016), emphasizes that the purpose of monitoring is to differentiate between areas where pollutant exposure levels exceed air quality standards and/or guideline.

Additionally, to understand the level of air pollution exposure in cities and urban areas is important; in terms of being able to verify areas that are exceeding an ambient air quality standard and identify if there is a need for public air quality agency to mitigate the corresponding pollutant (Mwenda, 2011; Murad and Pereira, 2019). Monitoring and assessment exposure of air pollution combine fixed monitors, low-cost sensors and other monitoring technologies with data transfer, quality assurance, statistical and numerical models as well as advanced computer platforms (Pattinson et al., 2014; Khuluse, 2017). Additionally, the above-mentioned methods are useful for processing, distributing and presenting data as well as modelling results for air quality exposure assessment.

2.5. AIR QUALITY MONITORING METHODS

2.5.1. FIXED SITE MONITORS

Developing and well-developed countries monitor air pollution using fixed monitoring stations that are mainly built by environmental or government authorities (Xie et al., 2017). Fixed site monitors are stationary equipment that consists of mobile units containing instruments to measure certain air pollutants (DEADP, 2018). According to Khuluse (2017), fixed site monitors are mostly restricted and built in locations characterised by heavy pollution sources, particularly in developing countries. Mwenda (2011), the limitations of resources and politics have had an impact on the number of stations commissioned and the quality of the data collected. Moreover, this monitoring method uses a different approach to determine pollutant concentrations as they follow different regional policies, which can differ, from one country to another (Weissert et al., 2020). Additionally, Pattinson et al. (2014), discovered that fixed monitors capture accurate measurements that are used to understand long-term air quality pollution. This practice is useful in indicating whether cities comply with the prescribed national ambient air quality standards. These monitors' data is critical since it is utilized for enforcement and is accepted in a court of law (Weissert et al., 2020).

They are not without limitations, however, in that they provide air quality data from a single fixed monitoring station, which does not represent local air quality (US EPA, 2019). As indicated by Sajani et al. (2004), these monitoring stations are characterized by measuring air pollution at a very low spatial resolution. The reason is that fixed monitors are fixed expensive because they require a range of infrastructure to operate with power connections and security arrangements (DEADP, 2018). Moreover, due to the size and cost of maintenance most cities can only afford a limited number of monitoring stations (Dias and Tchepel, 2018). Hence, the gaps in monitoring spatial variability of pollutants.

2.5.2. LOW-COST SENSORS MONITOR

Low-cost sensors are relatively new technologies that measure air pollutants and they cost much less than traditional air quality monitors do (Weissert et al., 2020). Low-cost sensor monitors entail deploying instruments for a short period of time at a temporary location before moving to another (Thongpllang, 2016); these deployments can last as little as a few hours or as long as a few days. For example, Cambridge University researchers used low-cost Alphasense sensors in the backpacks of cycling and walking students to map air pollution across the city (MacNaughton et al., 2014). The results showed that some parts of the city recorded levels ten times higher than that measured by the fixed monitoring station.

It is for this reason that Kumar et al. (2015), recommend the use of new low-cost sensor technologies such as low-cost portable devices with GPS for air quality exposure assessment and monitoring. In developed countries, the use of low-cost mobile monitoring equipment (MacNaughton et al., 2014; Alvear et al., 2016) has been observed. For instance, MacNaughton et al. (2014), designed a battery-powered mobile monitoring station to study the spatial variability of air pollutants. Likewise, Alvear et al. (2016), used a Toyota HiAce vehicle fitted with monitoring sensors to estimate the spatial variation of PM.

This monitoring method is important and useful because it covers many locations, quickly and more cheaply than deploying a fixed site (Thongpllang, 2016). For instance, spatial variation behaviour of air quality pollutants affects concentration levels and low-cost sensors allow responding to these challenges quickly. Randle (2016), on the other hand, argues that these low-cost sensors have both advantages and disadvantages. For example, they are unable to capture geographic variability across a broad spectrum. According to Alvear et al. (2016), these sensors can be a valuable first step in determining where to install fixed sites to measure the highest concentrations of pollutants. Nevertheless, they are not a long-term solution for understanding air quality accepted in a court of law (Weissert et al., 2020).

2.6. AIR QUALITY MAPPING TECHNIQUES

High-resolution maps of air pollution are needed for quite many reasons including to give accurate results in assessing exposure as part of epidemiological studies and to inform urban air quality policy and management (Briggs, 2000; Song et al., 2019). These maps can provide information on geographical variation status, not only on the spatial-temporal data trends that are usually provided by fixed monitoring stations (Briggs, 1997; Kumar, 2015; Gao et al., 2018). Briggs (2000) and Gao et al. (2018), discovered that air quality maps can be useful in terms of identifying pollution priority areas, defining at-risk groups, show changes in spatial patterns of pollution resulting from policy and other interventions. Xie et al. (2017), further state that such pollution maps can provide improved estimates of exposure. However, mapping urban air pollution might face several challenges; for instance, data on emission sources and pollution levels are often sparse (Longley et al., 2005).

Therefore, the introduction of low-cost sensors and GPS technology improved the availability of data on emission sources and pollution levels, providing a valuable data source for air pollution modelling (Beelen et al., 2013; Medeiros, 2020). However, this has been identified as the method that increases the data on emission source measurements but does not eliminate measurement sparsity. According to Schneider et al. (2017), this can be caused by the carriers of low-cost sensors and GPS, which mainly focus on exploring a specific area or covering the city roads. Balogun and Orimoogunje (2015), studies discovered that mapping air pollution is a flexible method for urban scale monitoring providing high geographic resolution maps with detailed spatial and temporal variation status. Spatial analysis and overlay techniques available in GIS provide powerful tools for such methods in mapping urban air pollution (Weng and Yang, 2006; ESRI, 2007)

According to US EPA (1998), the GIS application in mapping and modelling air quality transportation-related issues is traced as far back as early 1990. Furthermore, Briggs et al. (1997), identified that traditionally there are two general approaches to mapping ambient air quality: Inverse Distance Weighted (IDW) and Kriging Interpolation methods.

2.7. APPLICATION OF GIS IN AIR QUALITY MAPPING

Geographic Information System (GIS) is an important tool for scientific researchers in terms of data processing, analysing geographical distribution, mapping, monitoring and management of health pandemics (Longley et al., 2005; Kumar et al., 2015). GIS has proven to be the most applicable tool in various fields of study (ecology, waste management, criminology, and urban planning) to solve some of the problems in those fields (Chattopadhyay et al., 2010). Janssen et al. (2008), discovered that GIS can be used to examine the exposure assessment in support of both air pollution epidemiology and policy. In developed countries, it has been identified as a tool that is able to generate a high-resolution display of the spatial distribution of pollutants and behaviour occurrence (Li et al., 2019). Furthermore, GIS has been proven as the software technology that integrates baseline data and unique visualization of geographic analysis on the maps (Kumar et al., 2015).

Several scholars realised that assessing, monitoring, and mapping urban air pollutants requires spatiotemporal data management, which is provided by advances in GIS and earth observations (Longley et al., 2005; ESRI, 2007; Dubey, 2014). Chattopadhyay et al. (2010); Mwenda (2011), identified that it is important to understand the spatiotemporal behaviour of air pollutants in urban areas. Many developed countries of the world have in place programmes for monitoring the spatial distribution of urban air pollutants. According to Costabile (2010), these monitoring programmes were proven successful with the support of newly developed technologies such as GIS which is capable of mapping spatial variations of urban air pollution.

Regardless of the increase in urban development and anthropogenic activities, monitored data on urban air pollution are sparse in South Africa and many developing African cities (Gupta et al., 2010 and Li et al., 2019).). Hence, the collection of accurate and reliable data necessary for the evaluation of urban air quality with the support of newly developed technologies is therefore very important. According to Li et al. (2019), it is important to acquire spatial distribution information because of its flexible spatial data management and effective spatial data analysis methods in GIS. Subsequently, GIS is a flexible and dynamic technology that can integrate large quantities of geographic spatial data.

2.7.1. THE BENEFITS OF USING GIS ON AIR POLLUTION

GIS technology is capable of managing statistical and spatial data in terms of providing a tool that shows the relationship between poor air quality and the occurrence of human and environmental health issues (ESRI, 2007). Thus, the use of the GIS tool aids in monitoring pollutant emissions. According to Hurlock and Stutz (2004), this application can be used to ensure that no further pollution occurs. GIS tools help to locate the source of air pollutants and be able to monitor those sources for a change to conserve the quality of air. Additionally, modern technique such as GIS is capable of providing the geospatial distribution of pollutants over time and location and digital records, and provide maps as output (Agrawal et al., 2003; Hurlock and Stutz, 2004).

GIS is the software technology that integrates baseline data and unique visualization of geographic analysis on the maps (Kumar et al., 2015). Hurlock and Stutz (2004), concur that the geographical information science has become the most component of integrated transport, land use and environmental decision-making systems. Elliott and Wartenberg (1997) and Kumar et al. (2015), asserts that GIS integrating models are aimed at representing the spatial behaviour of traffic-related pollutants. Subsequently, it helps to monitor spatial-temporal scales and thus reduces the cost and time of field surveys (Kumar et al., 2015). Furthermore, GIS is an extension of new methods for environmental conservation of the future (Song et al., 2019).

Additionally, it is important to acquire spatial distribution information because of its flexible spatial data management and effective spatial data analysis methods in GIS (ESRI, 2007). A small but growing number of scientists have started experimenting with the use of interpolation methods of GIS monitoring air quality and others have looked at the spatial distribution of air pollution (Koas, 2010). A study by Ibrahim et al. (2012), has successfully applied GIS using the inverse distance weighted interpolation method to map the spatial distribution of criteria air pollutants in Peninsular Malaysia. Likewise, Longley et al. (2019), applied GIS using the kriging interpolation method to assess the spatial variability across multiple pollutants in Auckland, New Zealand. According to Briggs (2000), the GIS technique in the last few decades has produced a wide range of spatial interpolation methods. This study will adopt IDW spatial interpolation method with the application of the GIS framework to map and address the spatial distribution of ambient air quality, because of its practicability and applicability in the research study.

2.8. THE EFFECTS OF METEOROLOGY ON SPATIAL DISTRIBUTION OF AMBIENT AIR QUALITY

Meteorology plays a key role in the formation, transportation, and distribution of air pollutants (Madonsela, 2019). In addition, meteorological conditions in an area have a direct impact on the accumulation and spatial distribution of pollutants in the atmosphere (Borge et al., 2019). Borge et al. (2019) and Tharani et al. (2021), mentioned that the meteorological variables such as temperature, wind and precipitation influence the distribution of ambient air pollutants and their concentration levels. According to UCAR (2020), the wind transport air pollutants away from their source, causing them to be spatially distributed all over the area. Thus, wind speed and direction can influence the distribution of air pollutants, for instance, the higher the wind speed the more pollutants are distributed and the lower their concentration close to the source (Kandlikar, 2007). However, high wind speed can also generate dust, particularly in dry windy rural areas.

Kagabo (2018), identified that the spatial distribution and concentration of ambient air pollution can also be influenced either by the stability or instability of the atmosphere to absorb or disperse pollutants. Atmospheric stability or instability occurs when there is ground heat during the day the air becomes more instability, especially in the middle of the day (UCAR, 2020). Davis Instrument (2020), mentioned that air instability causes polluted air to be distributed as it moves from its source; in contrast, stable conditions often occur at night when the air is cooler. Air contaminants released in urban areas at night such as from home fires, are not easily distributed causing localised pollution. For instance, a study done by Kagabo (2018), in Kigali determining the spatial and temporal variation concentration of PM found that high concentration levels of air pollutants are caused by built-up of particles at night under inversion conditions and/or atmospheric stability.

In a similar study done by Lourens et al. (2011), in Gauteng, the spatial and temporal concentration variations are ascribed to differences in seasonal meteorological conditions as well as additional sources in winter, particularly in urban areas. Furthermore, Jury et al. (1990), identified that in Cape Town, the Table Mountain shielding properties and the climatic factors in winter influence the accumulation and distribution of air pollutants. For instance, during winter periods Cape Town experience the temperature inversion with prevailing windless conditions which results in the occurrence of brown haze smog, particularly in winter seasons (Walton, 2005; Madonsela 2019).

2.9. SPATIAL DISTRIBUTION OF AMBIENT AIR POLLUTANTS IN CITIES

Spatial distribution refers to a set of geographic observations clarifying the importance of the behaviour of extraordinary characteristics across different locations on the Earth's surface (King et al., 2014). The variation of the spatial distribution of urban air pollutants has become a widespread concern in several fields of study such as urban/rural planning, environmental science and medicine (Yang et al., 2016). Ibrahim et al. (2012), discovered that spatial distribution characteristics in air quality studies might be used to help in locating air quality monitoring stations. This technique can be helpful in predicting variations in the concentration of air pollutants due to changes in meteorology. In addition, this technique may include analysis of distributed pollutants across the globe and the investigation of movement as well as their influential factors (Jiang and Bai, 2018).

According to US EPA (2019), the spatial and temporal distribution of transport emissions are of key concerns. The meteorological patterns, high buildings and street canyons are likely to affect both the concentration and spatial distribution of air pollution emissions from mobile sources (Shi et al., 2019). Therefore, studying spatial distribution of air pollutants on the environment involves a multiscale approach. For instance, air pollutants emitted in the atmosphere can be distributed over a wide range of horizontal scale (Vardoulakis et al. 2003; Di Sabatino et al., 2018). Moreover, the pollutants that are transported to the city or are locally emitted they might be distributed at a horizontal scale, street canyons, neighbourhood, and/ or city (Di Sabatino et al., 2018).

According to Yang et al. (2016), their final spatial distribution is determined by several factors, such as the meteorology and morphological characteristics of the city, as well as the population density and the type, nature, and spatial location of sources. Vardoulakis et al. (2003), corroborated that the distribution of pollutants is strongly affected by variation in street canyons geometry, wind speed and direction, thermal stability conditions, tree planting and moving vehicles. Therefore, understanding the spatial distribution and temporal variation of air pollution contributes to meeting the sustainability development goal by implementing effective policies to mitigate air pollutants (Jiang and Bai, 2018).

2.10. A REVIEW OF STUDIES ON THE SPATIAL DISTRIBUTION OF AMBIENT AIR POLLUTANTS IN URBAN AREAS

The spatial distribution and characteristics of ambient air pollutants have been studied in most cities around the world and help in achieving the sustainable development goal. Table 2.1 below demonstrates several studies of ambient air quality that have been conducted on the spatial distribution of ambient air quality monitoring in urban areas. The table indicates the disparities in assessment and monitoring methods used, and how air pollution is distributed in a city for different air pollution gases and particulates in different seasons. In terms of the methodology, the majority of the studies reviewed used a modelling monitoring technique to determine the spatial distribution and characteristics of ambient air quality.

However, mapping ambient air quality studies in developing countries are few and needed. Because there has been an increasing number of air quality mapping studies observed of traffic-related pollutants globally, however in African developing cities mapping the spatial distribution to understand the spatial variability of ambient air pollutants is still limited (Han and Naeher, 2006; Khuluse, 2017). Whereases, Smallbone (1998); Mwenda (2011), emphasised that the ability to understand the spatial and temporal patterns of air pollution in urban areas, particularly for a traffic-related pollutants is increasingly important.

Schwela (2006), identified that most developing countries including African cities lack the capabilities to monitor air quality effectively. The limitations of resources, economic stability and politics have had an impact on the quality of data monitored/collected and Africa is no exception to this issue (Mwenda, 2011). A study done by Gebreab et al. (2015), found that mapping the spatial distribution of air quality is useful to understand population exposure as well as planning relevant air quality measures; however, in developing countries like West African towns, the major challenge to mapping air quality is the lack of GIS data. Several studies in developed countries consistently used GIS technology to produce an accurate mapping of the spatial distribution of air quality. Whereases, studies available in developing nations including African cities have looked at the modelling of the spatial variability of ambient air quality without mapping.

Table 2.1: Below shows, several studies done to determine the spatial distribution of ambient air quality.

REFERENCE	COUNTRY	POLLUTANT	AIM OF THE STUDY	METHOD	SEASON	SOURCE OF AIR POLLUTION
Moja and Godobedzha (2019)	South Africa (City of Tshwane)	PM	Spatial and temporal assessment of PM levels	TEOM and statistical analysis	All season	Industrial activities
Efe and Efe (2008)	Southern Nigeria (Warri metropolis)	PM	Differentiate distribution of PM between urban areas and the surrounding rural areas	Field measurement and statistical analysis	Summer and Winter	Industrial activities and heavy vehicular emissions
Tshehla and Wright (2019)	South Africa (Limpopo)	PM	To assess the spatial and temporal variation of PM	Air pollution model and kriging interpolation	Winter and summer	Major roads
Daful et al. (2020)	Kuduna Metropolis (Nigeria)	PM	to analyse the varying spatial relation between air pollutants	Pearson correlation and GWR (GIS)		
Song et al., (2019)	Jiangsu (China)	PM and NO_2	To analyse spatiotemporal charactersitics of air pollution	statistical software SPSS 22.0 and GrADS 19	Winter and summer	Residential activities
Adedeji et al., (2016)	Nigeria	NO_2	Mapping of Traffic-Related Air Pollution	Kriging interpolation and GIS	All season	Vehicle emissions
Kumar et al. (2016)	India (Mumbai)	NO_2	Air quality mapping using GIS	IDW and kriging interpolation in GIS	All season	Vehicle emissions
Tharan et al. (2021)	Coimbatore	PM_{10}	To determine the spatial distribution analysis of air pollutants and the impact of meteorological factors	IDW method using ArcGIS pro	All season	
Costabile et al. (2010)	China (Lanzhou)	NO_2	To investigate the spatial distribution of urban air pollution.	Diffusive samplers and statistical analysis	All season	Anthropogenic activities

2.10.1. STUDIES ON SPATIAL DISTRIBUTION OF PARTICULATE MATTER

Understanding the spatial distribution of ambient air pollution is crucial, as it helps to identify the sources of pollution with the influential factors behind the distributions of air pollutants in an area. With this in mind, this will help in policy formulation and decision-making on monitoring the air quality exposure. Table 2.1 above shows several studies conducted to determine the spatial distribution of particulate matter in South Africa and other countries.

Moja and Godobedzha (2019), conducted a study in the City of Tshwane, South Africa to identify areas of high PM concentration levels, which serves as an indicator of air pollution hotspots within the study area, by conducting a spatial and temporal assessment. The study used secondary data collected using the tapered element oscillating microbalance (TEOM) devices within the period of 2009-2014. Statistical modelling technique was used to determine the spatial distribution concentrations level. The results showed that poor air quality is not evenly distributed throughout the city but is localized in a few areas with large numbers of low-cost residential areas, and commercial and/or industrial areas. The study further demonstrated that high concentration levels are discovered in the late hours as well as during winter seasons.

Tshehla and Wright (2019), done a study in Limpopo, South Africa to assess the spatial and temporal variation of PM with similar findings. The Air Pollution Model was used to collect data and kriging interpolation method for modelling and analysis were used to generate hotspot areas. The model output was imported into GIS to spatially display the seasonal and annual impacts of PM concentration. Results revealed that PM concentration were higher closer to the source during the day and spatial distributed over wide area during the night particularly during winter months. Subsequently, Song et al. (2019), studied the spatiotemporal distribution of air pollution characteristics in Jiangsu Province, China; the results showed that high concentration level air pollutants were spatially distributed in the residential area. The study corroborated that the northwest wind prevails in winter can be attributed to spatially distribution of particulate matter.

In contrary, Efe and Efe (2008), in Warri metropolis differentiated the distribution of ambient air pollution between urban areas and the surrounding rural areas. The study generated data from field measurements and used statistical modelling technique to analyse data. Results revealed that urban areas are the most polluted whereases rural areas are least polluted. The study further demonstrated that this was caused by large amount of industrial operation and heavy vehicular traffic in urban areas. The findings of the study done at Coimbatore City by Tharani et al. (2021), corroborate these findings. The high concentration of PM_{10} pollutants was found in close proximity of major roads. The study further demonstrated that the spatial distribution of high PM_{10} concentration was mostly accredited with increased vehicular movement and presence of high buildings. Costabile et al. (2010) oppose in the study of investigating the spatial distribution of urban air pollution that the seasonal air pollutants were normally distributed in space. Thus, the spatial distribution of urban air pollution was governed by the spatial diffusion (i.e. relocation or expansion in the city) of emission sources, at least for its apparent average behaviour. Thus, the spatial distribution of particulate matter differs in a region depending on the emission sources together with meteorological conditions.

2.10.2. STUDIES ON SPATIAL DISTRIBUTION OF NITROGEN DIOXIDE

According to table 2.1 above Daful et al. (2020), did a study in Kuduna Metropolis to analyse the varying spatial variability of nitrogen dioxide with the use of validated portable pollutant monitors for data collection on the concentration of air pollutants. The study also used the Pearson correlation and Geographic Weighed Regression for data analysis. The collected data imported into GIS application to create shape files for analysis. Furthermore, the GWR model method revealed that the distribution of nitrogen dioxide varies spatially across Kuduna Metropolis and might be influenced by seasonal variation. Higher values were mostly in the central and southern part in close proximity of major roads. The study further demonstrated that the high concentration levels of nitrogen were most higher during winter season and lower during summer.

Additionally, Adedeji et al. (2016), in a study of spatial distribution of nitrogen dioxide using mapping technique which was carried out by use of kringing interpolation method in GIS software. This study aided to map the traffic-related air pollution concentration levels; therefore, results revealed that air quality in most areas is very unhealthy (regarded as not good for environment and human health). Kumar et al. (2016), in India (Mumbai) did a similar study with different results; the aim was to map air quality using GIS. Secondary data from National Environment Engineering Research Institute (EERI) and Brihanmumbai Municipal Corporation (BMC) were spatially interpolated using various interpolation techniques of ArcGIS such as kringing and Inverse Distance Weighted (IDW). Results of NO_2 were compared with air quality data of Maharashtra Pollution Control Board (MPCB) in the same region. Therefore, comparison of results showed good agreement for predicted values.

2.11. CONCLUSION

The reviewed studies reveal that the challenges of ambient air pollution and monitoring system is a challenge worldwide. It was discovered that traditionally air pollution is measured and monitored using designed dedicated instruments at fixed monitoring sites which are placed sparsely in urban areas. Air pollution has clear consequences for human health, animals, plants, and the environment, causing respiratory diseases and physiological dysfunction. As a result, it is urgent and important to establish an air quality monitoring and early warning system to assess the degree of air pollution scientifically and more accurately forecast air pollutant concentrations. Air pollution not only contributes to worsening environmental pollution in cities, but it also exacerbates the harm to human health and ecological balance. Citizens are increasingly concerned about air quality these days. Because of the high frequency of monitoring, research based on real-time ground-monitored data is important for better exploring detailed patterns (seasonal and diurnal), particularly at the city scale, for example, for medium- and small-scale areas. As a result, the threat of urban air pollution to the physical and mental health of city dwellers has grown in prominence, attracting considerable attention to the issue.

CHAPTER 3: METHODOLOGY

3.1. INTRODUCTION

The main purpose of this chapter is to discuss the research methods adopted for this study in mapping the spatial distribution of ambient air quality using GIS. Mapping the spatial distribution of air quality is important in establishing amongst others the source and behavioural patterns of pollutants. This section further entails the description of research design, data collection, and data analysis.

3.2. RESEARCH DESIGN AND METHOD

The study used a quantitative research method to investigate the spatial distribution of ambient air quality. In essence the quantitative research approach measures the real-time concentration of air pollutants in a determined location. Therefore, this research method is appropriate for the current study given that it seeks to determine the spatial distribution of air quality using the secondary data retrieved from the air quality monitoring stations using GIS. Thus, the current research method adopted for this study is fundamental in gaining a broader understanding of mapping the spatial distribution of ambient air quality in Cape Town CBD.

The study used secondary data retrieved from City of Cape Town (CoCT) Air Quality Monitoring stations. No primary data was collected. The ArcGIS pro was used in this research to examine the spatial distribution of air quality in the CBD of Cape Town. Moreover, air quality monitoring stations were selected and main road networks for mapping spatial distribution of ambient air quality. Therefore, this functionality allowed explicitly to explore spatial patterns of air pollution.

3.2.1. AIR POLLUTION MONITORING STATIONS

The City of Cape Town (CoCT) municipality monitors the Cape Town CBD's ambient air quality through a network of 2 Air Quality Monitoring (AQM) Stations (DEADP, 2016). Therefore, these two monitoring stations have been selected for analysis of the spatial distribution of air quality in Cape Town CBD. The first monitoring station is located at City Hall CBD, as the name suggests in the central business district on the grand parade to the west of the Castle of Good Hope centre. Another monitoring station is located at Cape Town foreshore, which lies on the waterways of Table Bay adjacent to the V&A Waterfront. Foreshore station is with the city centre behind with approximately 3.5km distance away from City hall station. These monitoring stations are located within the proximity of main roads. The location of these AQM in Cape Town CBD is shown in figure 1 below.

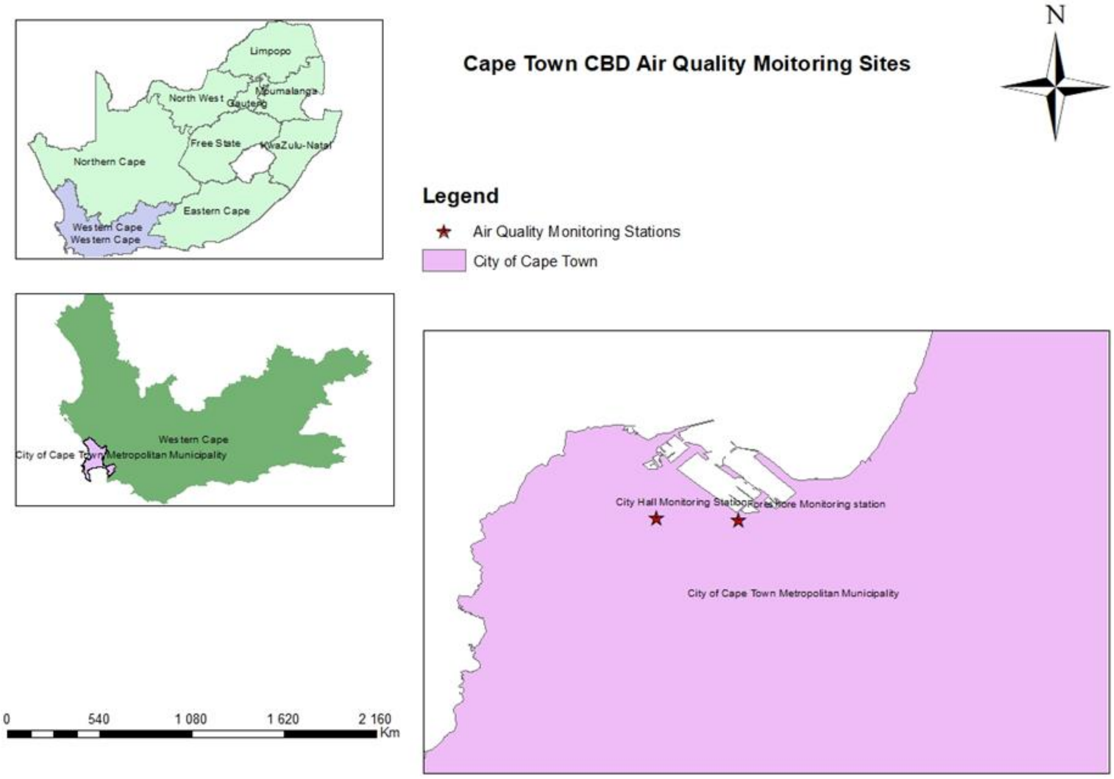

Figure 3.1: Cape Town CBD air quality monitoring stations

According to DEADP (2016), the Air Quality Monitoring stations monitors a wide range of anthropogenic and natural emissions. Subsequently, AQM are designed to measure exposure concentration level data of such anthropogenic and natural emission pollutants continuously during the monitoring period (Ibrahim, 2012). Furthermore, these AQM monitors a wide range of pollutants including PM, Carbon monoxide, sulphur dioxide, Ozone, oxides of nitrogen and Benzene (Gwaze and Mashele, 2018). These AQM stations functions remotely within a particular location that is connected in a network grid as illustrated in Figure 3.2 below. Therefore, the measured data is recorded at hourly intervals by City of Cape Town Municipality, however, for analysis of this study only peak hour measurements were used i.e., 06:00 to 09:00 morning peak hours and 16:00 to 18:00 which are afternoon peak hours.

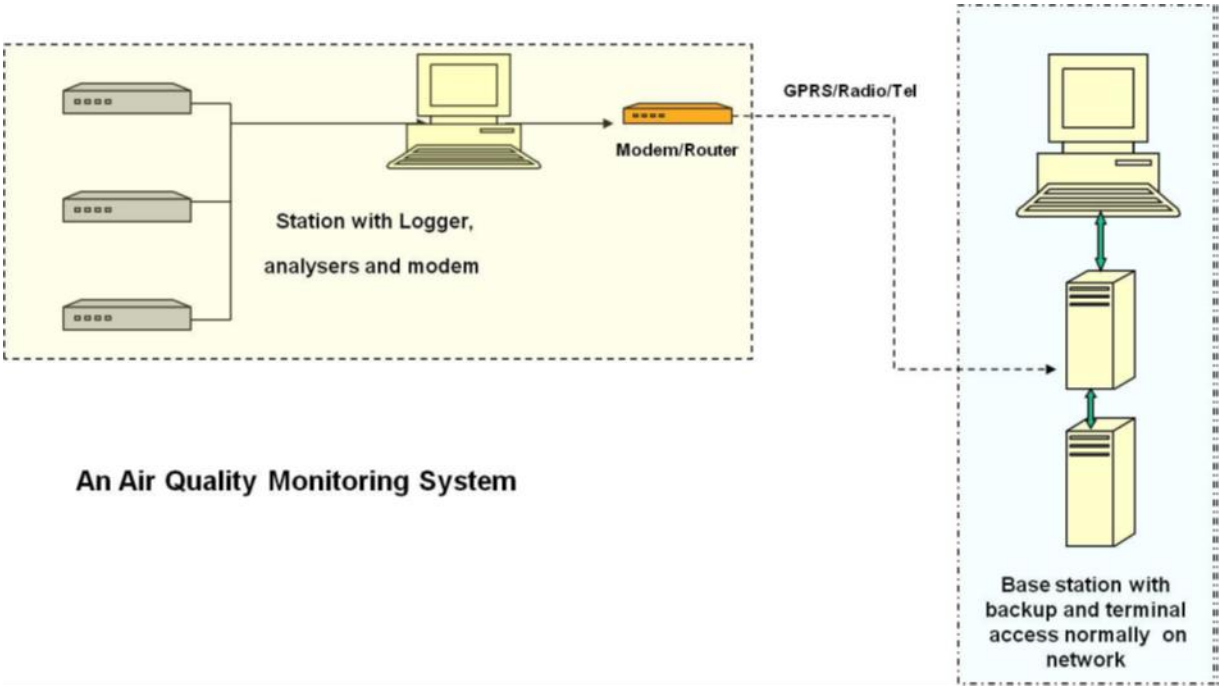

Figure 3.2: A typical AQM System Design (DEADP, 2016)

3.2.2. AIR QUALITY INDEX (AQI)

The City of Cape Town (CoCT) Metropolitan Municipality communicates the state of air quality to the public using Air Quality Index (AQI) system on its website. The AQI system of the CoCT municipality closely follows South African Air Quality Information System (SAAQIS) (DEA, 2009). SAAQIS normally presents the state of major air pollutants which could cause potential harm to human health should they reach unsafe exposure level.

3.3. DATA COLLECTION

The ambient air quality data was retrieved from the City of Cape Town Municipality air quality monitoring stations. These stations are located at Cape Town CBD to measure the exposure concentrations of ambient air quality. Amongst the measured pollutants substances are Particulate Matter (PM_{10}) and Nitrogen Dioxide (NO_2) which are pollutants of concern given that they are associated with traffic emissions. To this end, each station is designed to collect data of a particular pollutant. For instance, the Foreshore monitoring station is designated to measure PM pollutants whilst the City Hall monitoring station measures the (NO_2) pollutants. However, these stations collected data intermittently, as a result the current data obtained from the CoCT municipality mostly covered the years of 2017 to 2018 for both pollutants. The collected data was captured and cleansed with the help of Microsoft Excel spreadsheet 2013 in line with the objectives of the study.

3.4. DATA ANALYSIS

GIS spatial analysis was used in this study to determine the distribution of ambient air quality levels in Cape Town CBD. Therefore, the results of this research were presented and analysed using ArcGIS 10.8 pro a product of ESRI. This software can be used in mapping and analytics application to examine spatial relationships; predicts outcomes and make better data driven decisions. Moreover, this software handles multiple tables and relates them to each other with ease.

Additionally, the study used the ArcGIS for statistical purpose to model the pollution surface, based upon measurements at air quality monitoring sites. IDW modelling technique was deployed as it provides heat maps of pollution surface based on point measurements because IDW was more suitable for this study as it makes use of the existing monitoring station data.

Therefore, the development of a regression model and testing of a regression-mapping approach was carried out in all three centres using ArcGIS pro-10.8. In each centre a GIS was established, containing four main sets of data: main roads (e.g., road network, road type), altitude monitored data NO_2 and PM_{10} concentrations.

The geostatistical analysis functions in ArcMap pro 10.8 database development are either non-spatial (tubular) or spatial (containing locations). Therefore, graphs and heat maps were produced using the mean concentration of geostatistical analysis called IDW interpolation method. The conceptual model below (Figure 3.3) outlines the methodology adopted for exploring the spatial patterns of air pollution.

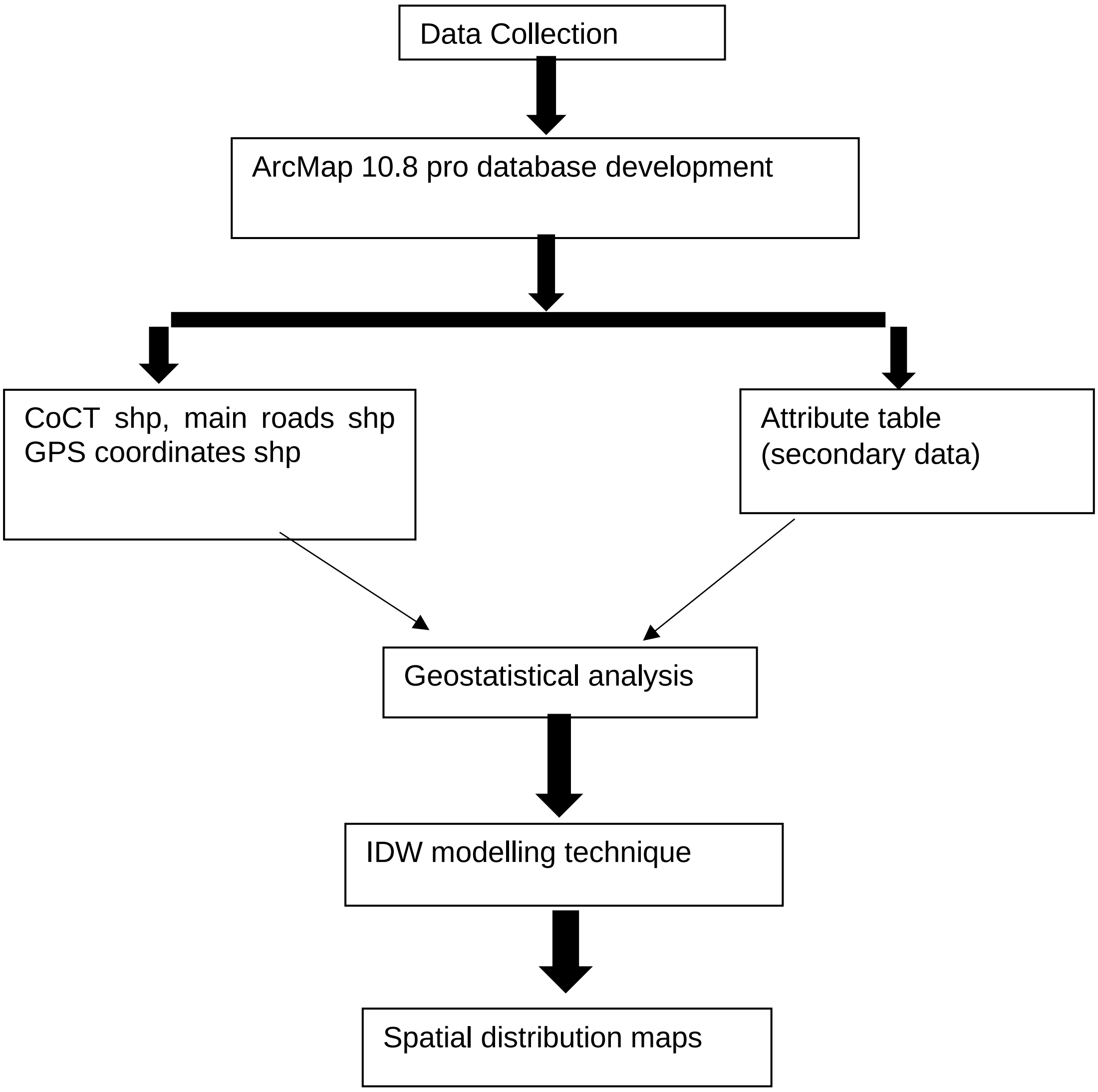

Figure 3.3: Conceptual model outlines the methodology adopted for exploring the spatial patterns of air pollution.

CHAPTER FOUR: RESULTS AND DATA ANALYSIS

4.1. NTRODUCTION

This chapter presents the results and discussion for all the data that was retrieved from City of Cape Town air quality monitoring stations. The chapter presents the results in a form of heat maps to show the spatial distribution of PM_{10} and NO_2 pollutants in two different seasons (summer and winter) in Cape Town CBD. The aim of this study was to map the spatial distribution of seasonal PM_{10} and NO_2 pollutants in Cape Town CBD using GIS coupled with secondary data retrieved from the City of Cape Town Municipality.

4.2. SEASONAL SPATIAL BEHAVIOUR CONCENTRATION OF PM_{10} AND NO_2 IN CAPE TOWN CBD, 2017-2018

During the rapid development of Cape Town's economy and society, urbanization has accelerated, and energy consumption has increased steadily. As a result, air pollution in the city has become a major threat to both physical and mental health. The seasonal spatial behaviour analysis for the concentration of PM_{10} and NO_2 of Cape Town CBD is represented in a form of bar graphs and line graphs. The bar graphs in figure 4.1 and 4.2 below shows the seasonal (winter and summer months) series dataset of monthly average concentration (table 4.1 and 4.2) of Cape Town CBD from 2017 to 2018. The line graphs in figure 4.3 and 4.4 shows the daily concentration exposure level of the PM_{10} and NO_2 during winter and summer months within 2017 and 2018. The x-axis in the graphs shows the seasonal variation (winter and summer months), whilst the y-axis demonstrates the pollutant concentration exposure level. The seasonal behaviour concentration demonstrates high levels of PM_{10} and NO_2 pollutants during winter which might be influenced and exacerbated by meteorological conditions such as low temperatures and low wind speed.

4.2.1. SEASONAL SPATIAL BEHAVIOUR CONCENTRATION OF PM_{10} AT CAPE TOWN CBD

Despite the importance of understanding and controlling air pollution in highly populated areas, interpreting levels of gaseous pollutants and particulates in the atmosphere is complicated by a number of factors including dominant natural and anthropogenic emissions, micro-meteorological processes, and chemical reactions that occur directly in the atmosphere. Therefore, to better explore and determine the seasonal (winter and summer) spatial distribution and behaviour characteristics of PM_{10} in Cape Town CBD during 2017- 2018 the table 4.1 and figure 4.1 below was used to show the concentration exposure levels. Both figure 4.1 and table 4.1 illustrate readings from Foreshore AQM which display the seasonal spatial behaviour of PM_{10} pollutant during winter (Jun, Jul and Aug) and summer (Dec, Jan and Feb) months within the years of 2017 and 2018.

Table 4.1: Seasonal concentration variation of PM_{10}

Monthly average concentration data of Foreshore AQM for PM_{10} ($\mu g/m^3$), 2017-2018				
Air Quality Monitoring station	**Year**	**Season**	**Months**	**Average concentration**
Foreshore AQM	2017	Winter	Jun	38.92
			Jul	33.83
			Aug	29.00
		Summer	Jan	26.61
			Feb	30.32
			Dec	28.06
	2018	Winter	Jun	32.35
			Jul	40.91
			Aug	23.08
		Summer	Jan	29.56
			Feb	33.87
			Dec	0.00

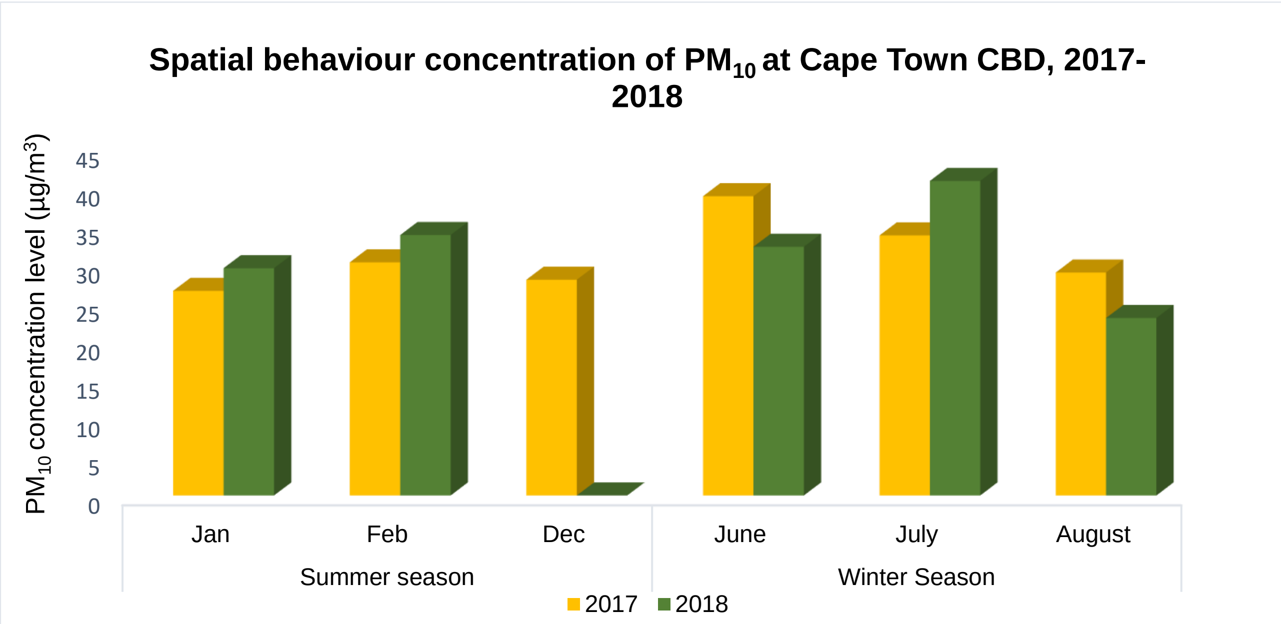

Figure 4.1: Seasonal spatial behaviour concentration of PM_{10}, 2017-2018

Figure 4.1 above demonstrated that the high concentration exposure levels of PM_{10} in 2017 peaked in Jun (winter) with 38.9µg/m^3. Whilst in 2018 during same season the pollutants concentration peaked in July with 40.91 µg/m^3. The occurrence of high concentration levels of PM_{10} in difference months of the years might be influenced by couple of factors, for example type of climate, changing state of weather and anthropogenic activities in that particular year. This result in a distinct variation of PM_{10} concentration to be in the ascending order of 2017<2018.

Moreover, the seasonal variation concentration of PM_{10} in figure 4.1 shows that high concentration levels were observed in winter and low concentration in summer months. Thus, the strong temperature inversion during winter season combines with prevailing windless conditions are attributed to the high concentration levels of PM_{10} Walton (2012). The findings of this study are consistence with previous studies done in cities of China by Jiang and Bai (2018) at Beijing; Li et al. (2019) at Weifang; and Song et al. (2019) at Jiangsu, observed high concentration levels during winter season and low concentration levels during summer season. The studies further demonstrated that the high concentration levels observed in winter were worsened by low temperatures and windless conditions. Cichowicz et al. (2017), corroborates the findings that the high concentration levels of PM_{10} in winter may be exacerbated by increase in emission from local furnaces as well the inversion temperature that may results in the smog events in most cities around the world. Wei et al. (2016); Jiang and Bai (2018); Li et al. (2019); Song et al. (2019), supported that the meteorological conditions such as temperature during winter season may results in air pollutants not easily dispersed, which might lead to high concentration levels of PM.

4.2.2. SEASONAL SPATIAL BEHAVIOUR CONCENTRATION OF NO_2 AT CAPE TOWN CBD

Increasing ambient NO_2 concentrations can have significant effects on respiratory health, particularly for children, the elderly, and individuals who are susceptible to asthma, pneumonia, bronchitis, etc. It can even cause death at extremely high levels and long-term exposure. The table 4.2 and figure 4.2 below shows the seasonal concentration variation behaviour of NO_2 pollutant during winter (June, July and August) and summer (Jan, Feb and Dec) months within the years of 2017 and 2018.

Table 4.2: Seasonal concentration variation of NO_2

Monthly average concentration data of City Hall AQM for NO_2 (µg/m^3), 2017-2018				
Air Quality Monitoring Station	**Year**	**Season**	**Months**	**Average concentration**
City Hall AQM	2017	Winter	Jun	34.43
			Jul	37.37
			Aug	38.41
		Summer	Jan	29.64
			Feb	33.51
			Dec	24.94
	2018	Winter	Jun	20.74
			Jul	31.65
			Aug	35.61
		Summer	Jan	26.97
			Feb	32.65
			Dec	21.36

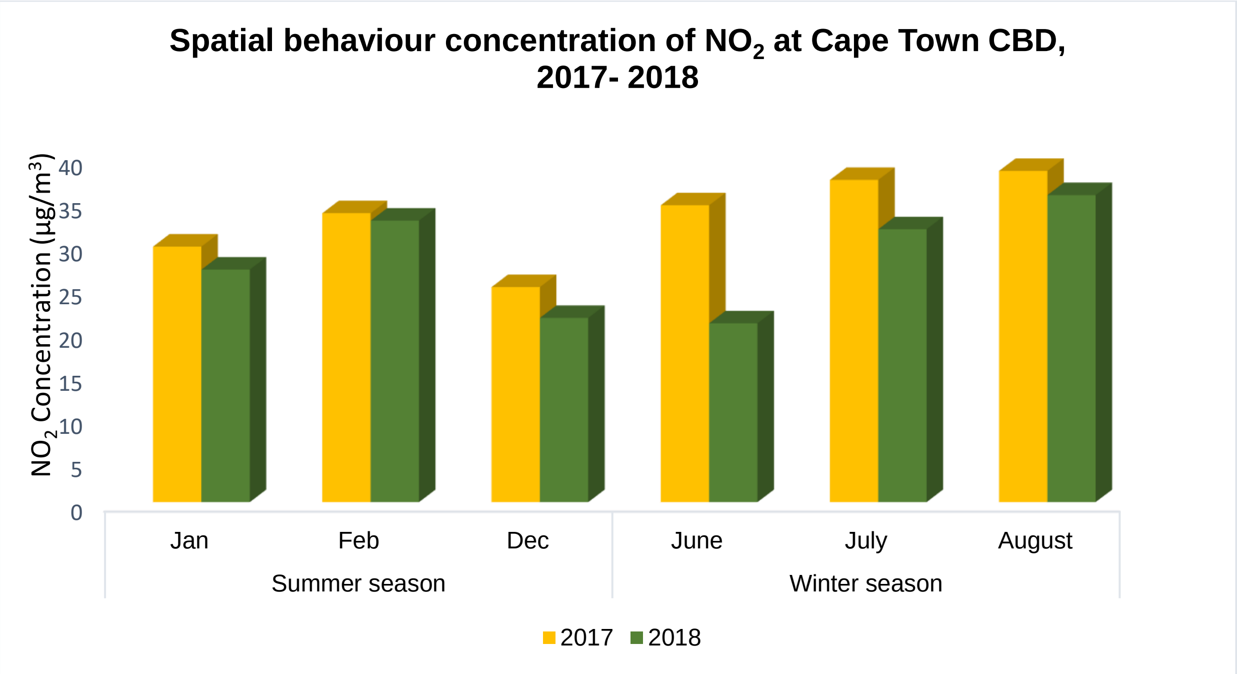

Figure 4.2: Seasonal spatial behaviour concentration of NO_2, 2017-2018

Figure 4.2 show that the is a seasonal variation in the concentration behaviour of NO_2 from 2017 to 2018. It was noted that winter season in both years recorded the highest concentration of NO_2, 38.41 µg/m^3 (2017) and 35.61 µg/m^3 (2018) all for the month of August. Furthermore, the results illustrate that the average concentration of NO_2 were low for the summer period (2017 and 2018) compared to winter average this might be attributed to the fact that Cape Town is dry summer subtropical climate (Mediterranean). Meaning more people tend to use private cars as oppose to summer as winter is characterized by heavy wind and rainfall (Singh et al., 2013). It was also observed that during summer the maximum concentration level peaked in February reaching concentration level of 33.51µg/m^3 in 2017 and 32.65µg/m^3 in 2018. The findings of this study are in line with the findings of the study done in Jiangsu city where the high concentration levels of NO_2 were reported during winter season reaching 54µg/m^3 concentration and low in summer season with an average of 40µg/m^3 (Wang et al., 2021). The study further discussed that the high concentration levels of NO_2 during winter were influenced by Jiangsu climate, in winter the city experience strong vertical temperature inversion layer which is making air pollutants not easily dispersed.

4.3. DAILY CONCENTRATION EXPOSURE LEVEL OF PM_{10} AND NO_2 AT CAPE TOWN, 2017-2018

In order to make predictions, it is important to select the appropriate time series models for the data. Using these time series models, environmental quality managers can estimate parameters according to evolving information needs. As well as providing early warnings to the respective population, the developed models can also be used by related bodies. Figure 4.3 and 4.4 below demonstrate the daily time series dataset for PM_{10} and NO_2 pollutant during winter (Jun, Jul and Aug) and summer (Jan, Feb and Dec) months at Cape Town CBD within the years of 2017 to 2018. Specifically, it shows the daily concentration exposure levels of Cape Town CBD from foreshore AQM (PM_{10}) and City Hall AQM (NO_2) measurements for 2017 to 2018.

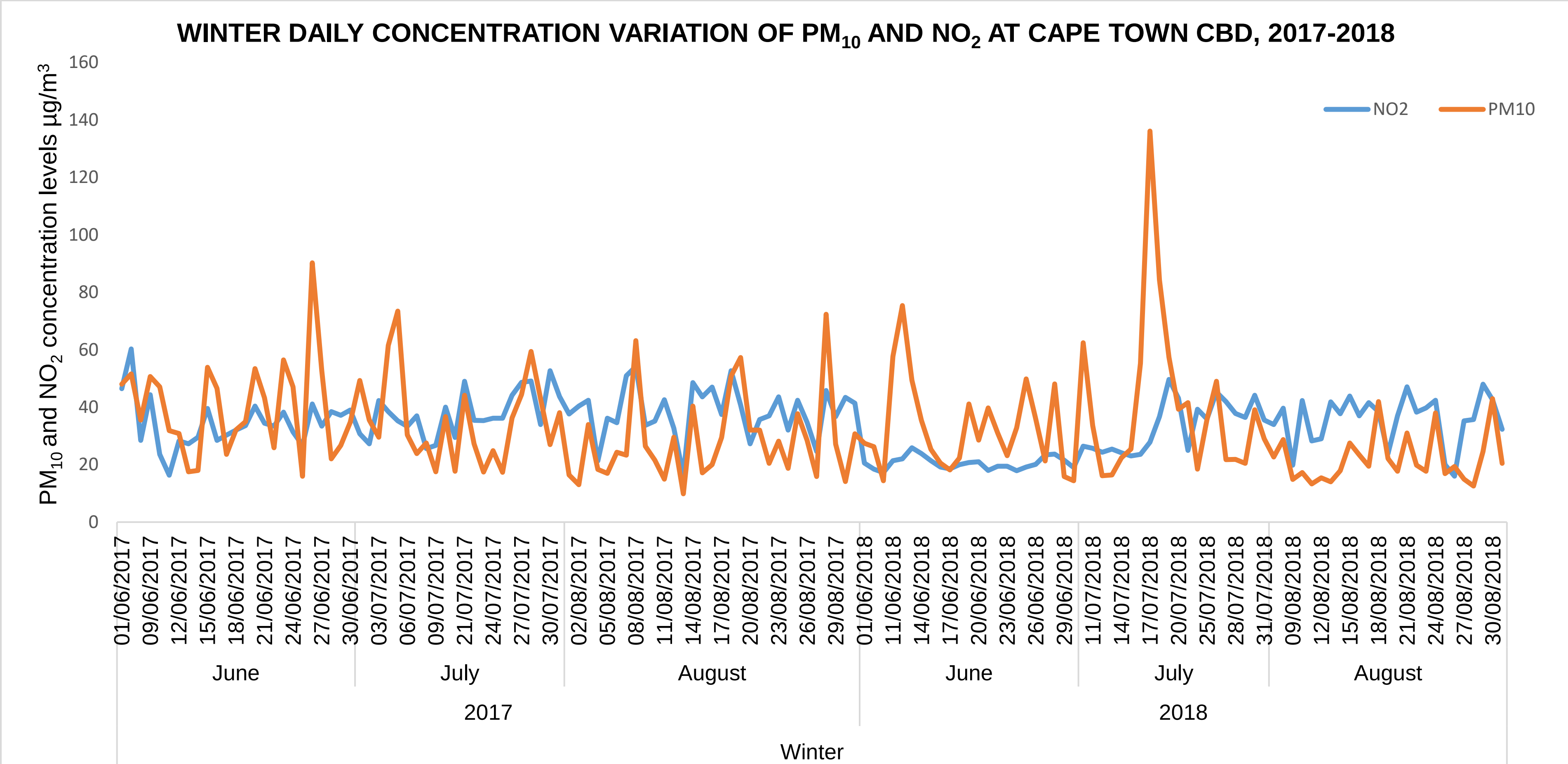

Figure 4.3: Daily concentration of PM_{10} and NO_2 pollutants during winter months at Cape Town CBD

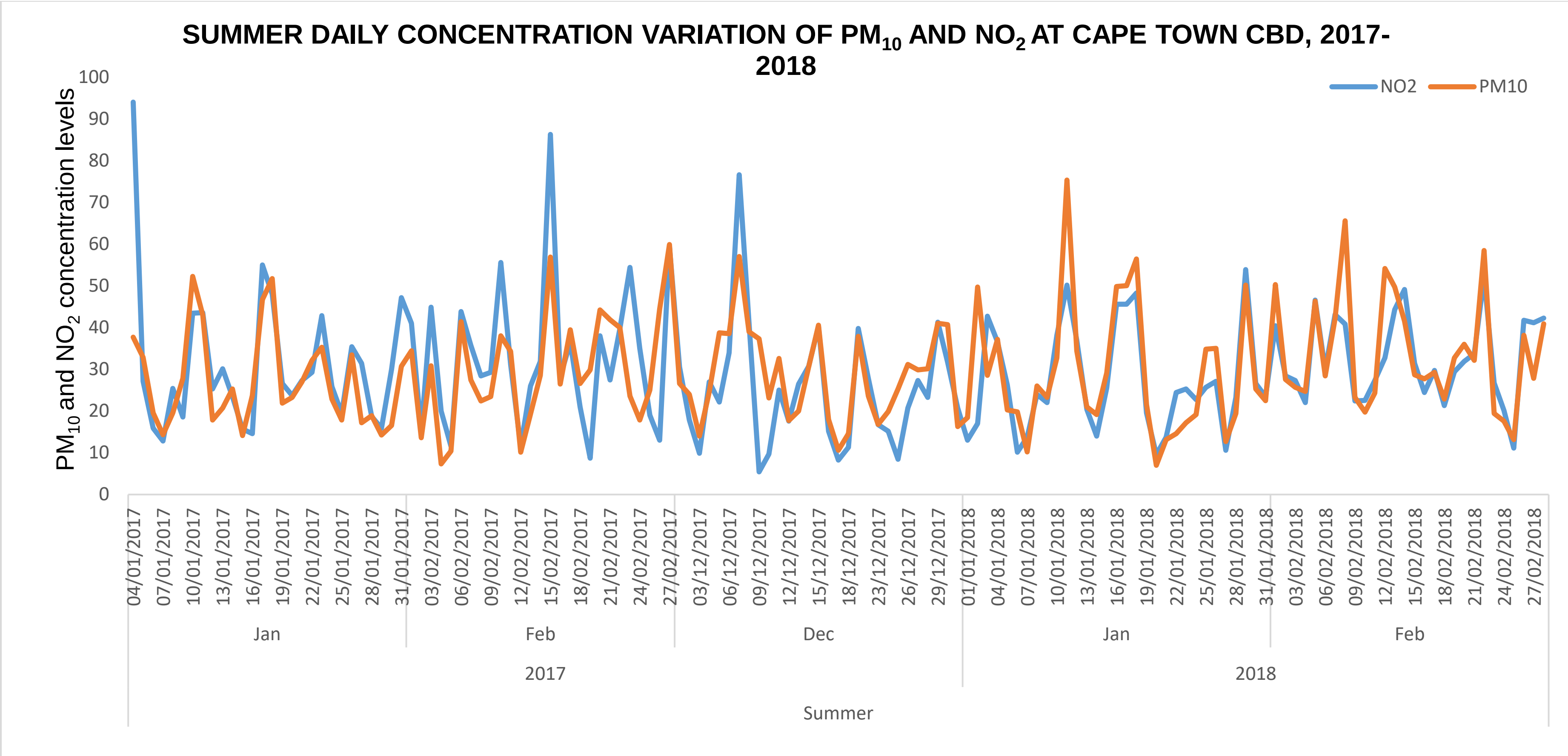

Figure 4.4: Daily concentration of PM_{10} and NO_2 pollutants during summer months at Cape Town CBD

According to figure 4.3 the PM_{10} pollutant has high concentration exposure levels that reaches 140µg/m^3 during winter month (Jul 2018). In other months and days, the concentration levels of PM_{10} and NO_2 almost behave the same with lowest concentration levels of less than 20µg/m^3. In corroboration with the results found by Tui et al. (2021), similar behaviour was found; the variation of the daily concentration of PM_{10} and NO_2 fluctuated significantly and had a high degree of similarity.

In comparison with winter months (figure 4.3) NO_2 pollutant has high concentration exposure levels that reaches 94 µg/m^3 during summer season (Jan 2017). It is notable that the high concentration exposure level of NO_2 were more severe in 2017 during summer in comparison to 2018. Although the NO_2 pollutant concentration peaked during summer days in 2017, the observation indicates that summer (figure 4.4) concentration exposure levels are low compared to winter concentration readings (figure 4.3). Additionally, according to observation (figure 9) during summer some days the concentration exposure level on NO_2 and PM_{10} have similar behaviour with lowest readings of less than 10µg/m^3. This indicates the better air quality in summer while in winter the levels are implying risky air pollution levels in the CBD. Moreover, the observations (figure 4.3 and 4.4) indicate that PM_{10} is the main pollutant of concern with high concentration recorded in the CBD particularly during winter months. The above results can be collaborated by the previous results from figure 4.1 and 4.2 which depicted that winter had higher concentration levels.

4.4. SPATIAL DISTRIBUTION OF PM_{10} AND NO_2 ($\mu g/m^3$) DURING SUMMER AND WINTER MONTHS' SEASON IN CAPE TOWN CBD, 2017 TO 2018

Considering the spatial characteristics of air pollution in cities can give us a better understanding of how the city as a whole is affected by air pollution, help identify the sources of urban air pollution, and help develop practical policies to control air pollution. As a result, such research has a significant impact on urban sustainability. Spatial interpolation maps were used to illustrate the air pollution exposure to PM_{10} and NO_2. The heat maps below show how pollutants varied across the CBD of Cape town during the summer and winter months of 2017 and 2018. An elevated concentration of the pollutant of concern indicates the hazardous zones, indicated by the colour red on the heat maps. In contrast, yellow indicates an exposure level of an average to middle concentration, whereas green indicates a low concentration of a pollutant, which identifies a zone that does not constitute a hazardous situation.

4.4.1. SPATIAL DISTRIBUTION OF PM_{10} ($\mu g/m^3$) DURING SUMMER SEASON IN CAPE TOWN CBD

High traffic volume and excessive pollutant emissions have been associated with the rapid development of Cape Town's economy and urbanization process, resulting in serious air pollution issues and hindering sustainable development. The figure 4.5 below show the seasonal variations in PM_{10} concentrations are essentially similar, and the seasonal variations' characteristics are as follows.

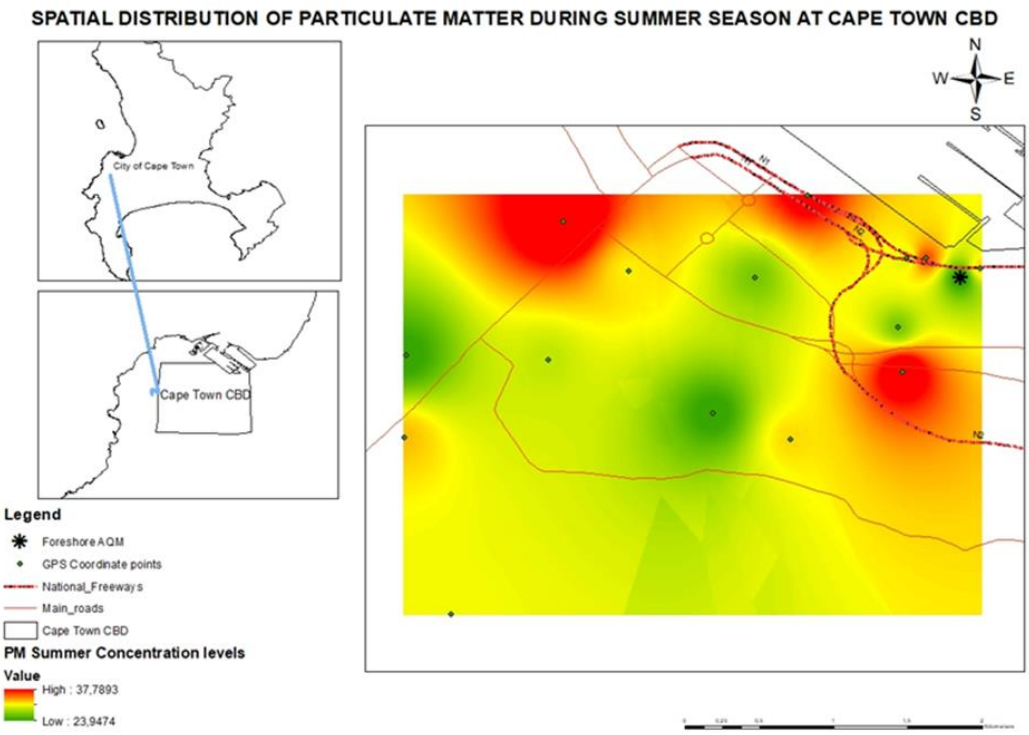

Figure 4.5: Spatial distribution of PM_{10} during summer season

Figure 4.5 above demonstrate mapping of the spatial distribution of PM_{10} concentration recorded at Foreshore AQM station within the Cape Town CBD from 2017 to 2018. The mapping outcome of summer PM_{10} pollutants generally indicate variability in spatial distribution. According to the figure 4.5 Foreshore monitoring station recorded low exposure concentrations (23.94 µg/m^3) of PM_{10} and it was observed that the is an increase in concentration when moving north and eastern part of the map. It was also noted that the high concentration of PM_{10} were found in close proximity of national highways and traffic intersection entering CBD which recorded 37.78 µg/m^3. This demonstrates that the national freeways, main roads, and traffic intersections entering CBD can be described as hazardous delineated zones. The findings of this study are in line with a study conducted in the areas of Bengaluru City where it was established that national highways and traffic intersection recorded high spatial distribution concentration of PM_{10} due to high traffic volume (Bozyazi et al., 2000).

Similar observation was found in a study done at Coimbatore City by Tharani et al. (2021), that PM_{10} pollutants was spatially distributed in close proximity of major roads. The study further demonstrated the spatial distribution of high PM_{10} concentration was mostly accredited with increased vehicular movement and presence of high buildings. Tshehla and Wright (2019), done a study of spatiotemporal distribution of air pollutants corroborated that the high concentration levels of PM_{10} were observed closer to the source of pollution. According to CoCT (2012), approximately 60% of vehicular traffic movements from Cape Metropolitan Areas are heading to Cape Town CBD. Thus, the traffic emissions might be the source of air pollution in the CBD because of the ongoing and coming traffic congestion (Kandlikar, 2007). As presented for instance, by the analysis in Figure 4.5 that the hazardous delineated zone is found to be in close proximity with the traffic intersection and national highway entering the CBD.

Moreover, Cape Town experiences a wind force called ‘Cape Doctor’ during period that is said to clear all air pollutants in the city offering amazing clear sky (Weather Services, 2019). The direction of this wind force is from South to East (‘South Eastern wind’) during warm summer seasons (Walton, 2005). Therefore, due to the wind force and direction that blows from False Bay and funnels through Cape Town City bowl to Blouberg, wind can be a factor that spatially distribute the air pollutants. Consequently, Kandlikar (2007), corroborate that meteorological factors such wind speed and direction have the aptitude to spatially disperse air pollutants. Thus, the variability in spatial distribution of pollutants at Foreshore AQM.

4.4.2. SPATIAL DISTRIBUTION OF PM_{10} ($\mu g/m^3$) DURING WINTER SEASON IN CAPE TOWN CBD

The spatial distribution analysis in air quality studies are essential and helpful in predicting seasonal variations in the concentration of air pollutants due to changes in meteorology. By mapping the spatial distribution, it will help us to understand the distributed pollutants across city and the investigation of movement as well their influential factors. Figure 4.6 below shows the winter seasonal variation characteristics of PM_{10} concentration.

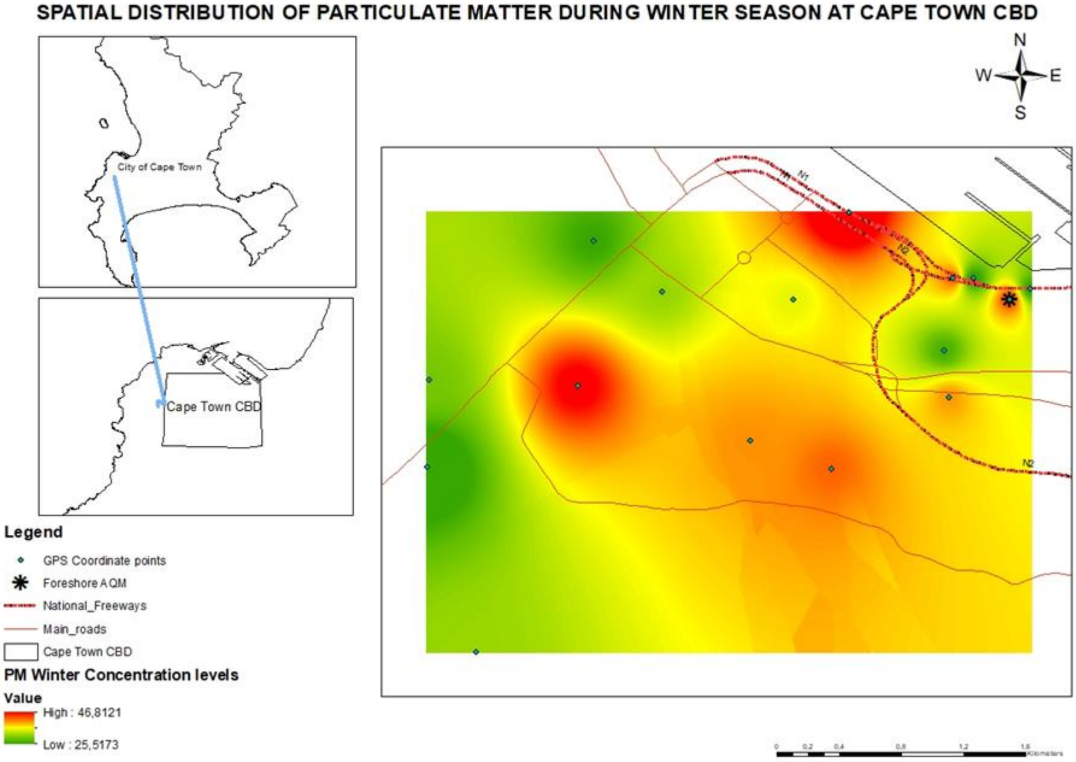

Figure 2.6: Spatial distribution of PM_{10} during winter season

The above figure 4.6 shows the analysis of winter spatial distribution of PM_{10}. The heat map illustrates the outcome of the pollutant that the Foreshore monitoring station recorded during winter months from 2017 to 2018. Winter spatial distribution of PM_{10} shows a distinctive spatial distribution compared to summer season. In this season the pollutant maximum concentration exposure level increase is almost double (46.81 $\mu g/m^3$) the records of the summer season. A study done by Chen et al. (2013), reported similar trend whereby particulate matter significantly increasing over the winter seasonal period. Another recent study undertaken in the Western Cape neighborhoods observed that the change of season generally affects the pollution exposure levels (Madonsela et al., 2022).

The results from this current study indicates that in contrast to summer observations the maximum concentration levels were relatively higher in Foreshore air quality monitoring station during the winter season with an increase observed when moving to south eastern side of the map. Thus, in winter the PM_{10} high concentration exposure levels are spatially distributed in the inland side closer to residential and/or high buildings.

Song et al. (2019), studied the spatiotemporal distribution of air pollution characteristics in Jiangsu Province, China; the results showed similar trend of highest readings of PM_{10} pollutant in the inland side. The study corroborated that the northwest wind prevails in winter can be attributed to spatially distribute the air pollutants in the northern part of Jiangsu that is close to the inland. Furthermore, Jiangsu has rainy conditions during winter season which results in a strong vertical temperature inversion layer, making air pollutants difficult to disperse (Song et al., 2019). Thus, Jiangsu winter condition is similar to Cape Town winter conditions with strong temperature inversion that combines with prevailing windless conditions that prevents air pollutants from dispersing upwards (Walton, 2005). These high levels of air pollution are primarily accountable for brown haze episodes in the CBD which result in poor visibility. The pollutants distribution can be attributed to low wind speed and direction that favour the accumulation of pollutants that is mostly experienced during winter seasons (Birgen, 2017).

In summer season the opposite situation occurred where the temperature was high with a high wind speed called “cape doctor’ therefore the PM_{10} pollutant was also reduced and behaved different compared to winter season. In a nutshell, the high concentration levels of PM_{10} during winter in the CBD are likely to be influenced by pollution from motor vehicles as the source of pollution and meteorological factors (i.e. wind speed and temperature).

4.4.3. SPATIAL DISTRIBUTION OF NO_2 ($\mu g/m^3$) DURING SUMMER SEASON IN CAPE TOWN CBD

Taking into consideration the location of the air quality monitoring station, NO_2 concentrations are lower in the west and higher in the east as illustrated in the figure below. Figure 4.7 below shows seasonal variations in NO_2 concentrations are essentially similar with PM_{10}, and the seasonal variations' characteristics are as follows.

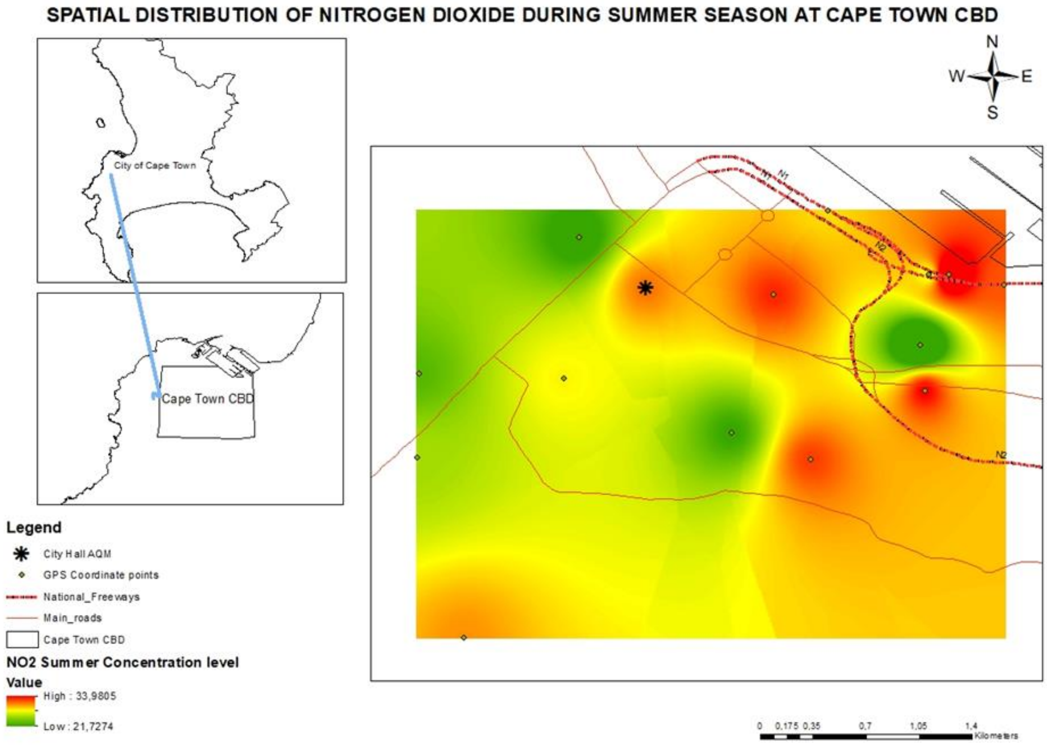

Figure 4.7: Spatial distribution of NO_2 during summer season

Figure 4.7 shows the spatial distribution of NO_2 during summer season in Cape Town CBD of 2017 to 2018. Among two monitoring stations located within the Cape Town CBD, one monitored the nitrogen dioxide pollutant for only the period of January 2017 to December 2018. Therefore, the study used the measurements between these years for winter and summer season for data accuracy. The heat map in figure 4.7 illustrate the outcome of summer seasonal distribution of NO_2 concentration at City Hall AQM station within Cape Town CBD. The City Hall monitoring station recorded high exposure concentrations (33.98 µg/m^3) of NO_2, with an increase in exposure concentration observed when the distance increases towards the north eastern and south eastern side of monitoring station in close proximity to national highways and traffic intersections.

The findings are similar to a study conducted by Adedeji et al. (2016), in Nigeria, Metropolis that the highest concentration of NO_2 were observed in the south eastern part in close proximity of major roads that are attributed with high traffic volume. Nevertheless, in a study done in Jinan City determining the spatial characteristics of environmental air quality the NO_2 pollutant was higher in the North eastern part and central parts of the map (Wang et al., 2021). The study further demonstrated that the direction of the pollutant distribution might be related to industrial production that are located in the north eastern part of the city.

In comparison with PM_{10} summer spatial distribution demonstrated in Figure 4.5 above, the spatial distribution of NO_2 almost behaves similar to PM_{10} towards the national highways, traffic intersections and main roads. That is, these two pollutants are both concentrated towards the traffic intersections. The discovery of a correlation reflected in similar behaviour between PM_{10} and NO_2 pollutants validates a long-standing relationship between the two pollutants (Pineda et al., 2018; Madonsela, 2019). The observed correlation might be engendered by the fact that NO_2 has been identified as a secondary precursor for particulate matter (Pineda et al., 2018; Madonsela et al., 2022), and these pollutants are both associated with traffic-related emissions primarily emitted from the combustion of motor engines Keen and Altieri, (2006). According to the figure 4.7 national highways and major roads can be identified as hotspot areas during summer season; the results of this study corroborate this finding.

Moreover, the south-easterly wind force known as the 'Cape Doctor' that blows during the summer months can be credited to spatially distribute the pollutants of PM_{10} and NO_2. In view of the above, numerous scholars suggest that the most important constraints on air pollution dispersion throughout the summer are meteorological variables such as wind speed and topographically induced flows (Wei et al., 2016; Jiang and Bai, 2018; Wang et al., 2021).

4.4.4. SPATIAL DISTRIBUTION OF NO_2 ($\mu g/m^3$) DURING WINTER SEASON IN CAPE TOWN

The spatial distribution of transport emissions is of key concerns. The meteorological patterns, high buildings and street canyons are likely to affect both the concentration and spatial distribution of air pollution emissions from mobile sources.

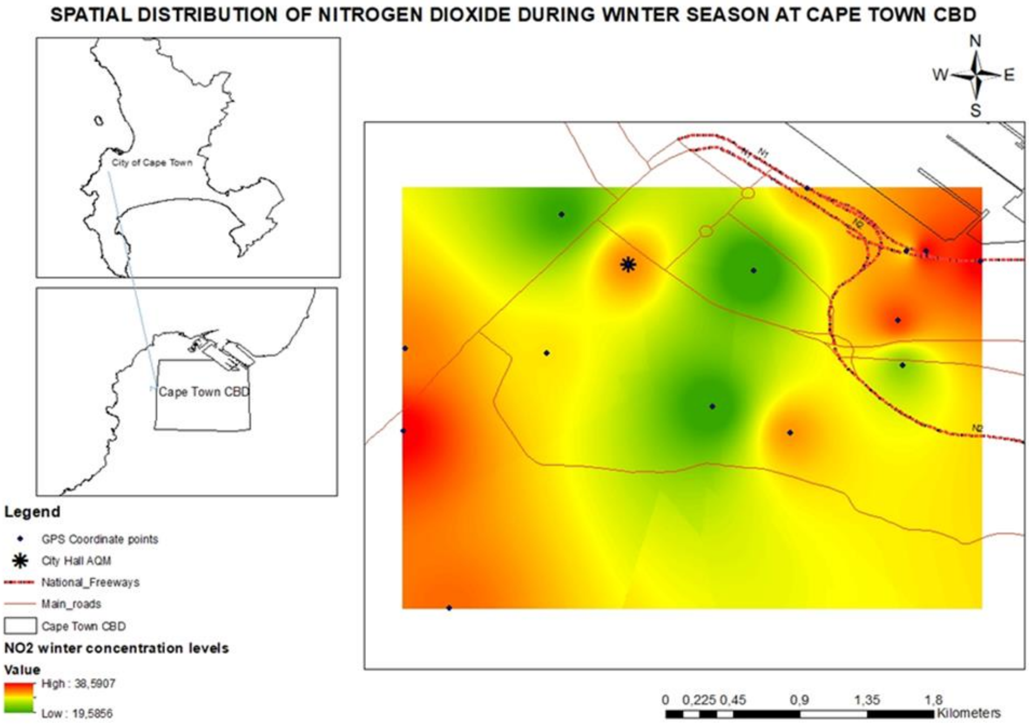

Figure 4.8: Spatial distribution of NO_2 during winter season

The above figure 4.8 above shows the results of winter seasonal spatial distribution of NO_2 in the Cape Town CBD for the period of 2017 to 2018. The heat map outcome of winter NO_2 pollutants from the City Hall AQM station generally indicate variability in spatial distribution. Figure 4.8 above shows that the City Hall monitoring station recorded high exposure concentrations (38.59 µg/m^3) of NO_2, it was observed that the is an increase in concentration when moving on the south western side of the map. Subsequently, high concentration exposure levels were also observed in close proximity of national highway (N1) and traffic intersection entering the CBD in the north-eastern side of the map. The findings of this study are in line with a study done by Moja and Godobedzha (2019), which was conducted in the City of Tshwane, identified that poor air quality is not evenly distributed throughout the city but localised in few areas with large numbers of residential areas and commercial activities particularly in winter. Similarly, observations, made by Moja and Godobedzha (2019), figure 4.8 indicate that the hazardous delineated zones are mostly marked in close proximity of residential areas (South western side of the map) and the harbour industrial areas in (North eastern side of the map). This is partly because stable meteorological conditions in winter do not promote the distribution of pollutants (Lourens et al., 2011).

These high concentration levels close to the harbour commercial areas may be influenced by the presence not only shipping emissions, but also other sources such as heavy-duty vehicles associated with port activities. A study done by Tularam et al. (2020), at Durban, South Africa highlighted the importance of harbour variable which serves as a proxy for NO_2 concentration.

In addition, the analysis in figure 8 indicated that the maximum concentration of ambient NO_2 levels were relatively higher in winter (38.59 µg/m^3) than in summer (33.98 µg/m^3). This can be attributed to the Table Mountain shielding properties and the climatic factors in winter that influence accumulation and distribution of air pollutants (Jury et al., 1990). Likewise, Wang et al., (2012) substantiate that the stable meteorological conditions are a contributing factor towards pollutant level increase during the cold (winter) seasons.

The maximum concentration level results indicate that the NO_2 concentration level trend is comparable to results obtained elsewhere, where high exposure levels of NO_2 were discovered during the winter season compared to the summer season (Levy et al., 2014; Rabiei-Dastjerdi, 2022). A study done by Zheng et al. (2018), emphasised that in winter season the pollutants are not easily washed away hence some cities experience brown-haze smog episodes. Correspondingly, in a study of spatiotemporal variation characteristics of air pollutants in Shijiazhuang City, the distribution of NO_2 was more severe in the north-eastern part of the map (Tui et al., 2021). Reason being in the north-eastern side there are industrial activities sources and large vehicle.

4.5. CONCLUSION

The spatial distribution and behaviour characteristics of ambient air quality (PM_{10} and NO_2) at Cape Town CDB were investigated by means of ArcGIS to map spatial distribution. The findings of the study show a distinct spatial variation that PM_{10} was the main pollutant in the CBD with high concentration between summer and winter within 2017 and 2018 and NO_2 pollutant was lighter. A large number of studies has shown that there are obvious seasonal differences in the distribution of air pollutants. The finding of this study indicated that meteorological conditions such as wind speed and temperature have a correlation close with the ambient air pollutants and play an important role to spatial distribution of PM_{10} and NO_2. Although the meteorological factors are not studied in this study, the findings were comparable with others studies conducted globally. Moreover, the national traffic roads entering the CBD, industrial harbour and dense residential areas with high buildings were considered in ascertaining as the pollution hotspot in the CBD.

CHAPTER FIVE: CONCLUSION AND RECOMENDATIONS

5.1. INTRODUCTION

This chapter provides the conclusion and recommendations for the research study. This study was set out to map the spatial distribution of ambient air quality in Cape Town central business district. The aim of the study was to map spatial distribution of PM_{10} and NO_2 pollutants in Cape Town CBD using GIS coupled with already existing secondary data (raw data) retrieved from City of Cape Town Municipality air quality monitoring stations. It is important to step back and assess if the study has achieved the aims and objectives of the study as set out in the introductory chapter. The three main objectives of the study were:

- To investigate and map the spatial distribution of PM_{10} and NO_2 in the CBD.
- To determine the spatial behaviour of PM_{10} and NO_2 concentration in the CBD.
- To assess the seasonal (winter and summer) distribution of PM_{10} and NO_2.

Below the conclusion remarks and key findings are provided:

5.2. KEY FINDINGS

- Regarding the seasonal spatial behaviour concentration of PM_{10} and NO_2 the average monthly concentration in Cape Town CBD has gradually increased during winter season in 2017 and 2018. The meteorological conditions such as low temperature and windless conditions during winter season at Cape Town CBD could be attributed to high concentration levels of these pollutants.
- In 2017 the average monthly concentration of PM_{10} peaked in June (winter) with 38.9µg/m^3 and NO_2 peaked in August (38.41µg/m^3). Whereases, in 2018 the high concentration levels of PM_{10} were observed during July (40.91µg/m^3) and NO_2 in August (35.61 µg/m^3).
- The summer results showed low monthly average concentration levels compared to winter months. This indicate that the is better air quality during summer months while in winter the levels are associated with risky air pollution levels at Cape Town CBD.
- Additionally, the observation of this study indicates that PM_{10} pollutant is the main pollutant of concern with high concentration levels recorded at Cape Town CBD particularly in winter whilst NO_2 was lighter.
- Regarding the spatial distribution, the study discovered that during summer season the PM_{10} and NO_2 pollutant almost behave the same with high concentration levels being spatially distributed in close proximity of national highways and traffic intersection on the eastern part of the map. Moreover, the south-easterly wind force known as the 'Cape Doctor' that blows during the summer months could be credited to spatially distribute the pollutants of PM_{10} and NO_2. Whereases, during winter season

PM_{10} and NO_2 were generally observed higher in the inland side in close proximity of residential areas.

5.3. CONCLUSSION

Air pollution is an important environmental problem that endangers urban development. The various scholars have studied more about the air pollution exposure concentration levels and spatio-temporal variation of air pollutants in urban areas, mapping the spatial distribution have not been considered, particularly in developing countries especially within the African continent. Due to the fact that the mapping of spatial distribution of ambient air pollutants has not been considered as a tool for air quality monitoring, this research then has established the importance of investigating the spatial distribution of ambient air pollutants in urban areas. The study findings discovered that considering the spatial distribution characteristics of air pollution in cities can give us a better understanding of how the city as a whole is affected by air pollution, help to identify the sources of urban air pollution, and help to develop practical policies to control air pollution.

The greater the spatial detail provided can be advantageous in improving estimation based on interpolation between ground observation and dispersion models. The IDW interpolation analysis was performed using ArcGIS pro to estimate and investigate the spatial distribution and behaviour characteristics of ambient air quality. The results of the study revealed that the spatial distribution of ambient air pollutants vary dramatically across the CBD with different geographical areas and the relationship merges to be stronger in areas of high traffic volume movement. Additionally, according to the findings of this study is it important to conclude that the use of GIS can be effective and efficient to examine and monitor the spatial distribution of ambient air pollutants over a large are.

5.4. RECOMENDATIONS

The spatial distribution analysis in air quality studies is essential and helpful in predicting long term variation in the concentration of air pollutants beyond the monitoring sites due to changes in meteorology. However, the meteorological factors are not studied in this study, the findings were comparable with other studies conducted globally. Therefore, this study strongly recommends the use of meteorological data to study the spatial distribution variability of air pollutants in a central business district. Moreover, there are several possibilities for extending the study analysis to be more detailed if this is required. For instance, this can be achieved by combining the fieldwork and secondary data. Different datasets should be used in order to perform spatial distribution behaviour analysis by detecting the change over a longer period so that a trend can be obtained. If funds were available, a fieldwork data collection could have been carried out to collect primary data with a lot of other information instead of relying on secondary data.

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APPENDIX A: CONSENT APPROVAL LETTER

CITY OF CAPE TOWN
ISIXEKO SASEKAPA
STAD KAAPSTAD

CITY HEALTH

Dr Natacha Berkowitz
Epidemiologist: City Health

T: 021 400 6864 **F**: 021 421 4894
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Ref: 24882 2020-09-08

RE: Mapping the spatial distribution of ambient air quality in Cape Town CBD using GIS

Dear Ongeziwe Ndletyana

Your research request has been approved as per your protocol. Please refer to the subsequent pages for the approval of any facilities or focus areas requested. Approval comments on any proposed impact on City Health resources are also provided.

Please contact Mr Ian Gildenhuys (Ian.Gildenhuys@capetown.gov.za) for access to required air quality data

Please note the following:

1. A copy of the final report must be uploaded to http://web1.capetown.gov.za/web1/mars/ProjectClosure/UploadReport/0/8294, within 6 months of its completion and feedback must also be given to the clinics involved.
2. Your project has been given an ID Number (8294). Please use this in any future correspondence with us.
3. No monetary incentives to be paid to clients on the City Health premises
4. If this research gives rise to a publication , please submit a draft before publication for City Health comment and include a disclaimer in the publication that "the research findings and recommendations do not represent an official view of the City of Cape Town "

Thank you for your co-operation and please contact me if you require any further information or assistance.

Kind Regards
Dr Natacha Berkowitz Epidemiologist: City Health

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