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UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Evaluation of the implementation of the first-generation Waterberg-Bojanala priority area air quality management plan (AQMP)

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This research report is submitted to the Faculty of Science in partial fulfilment of the requirements for the degree of Master of Science in Environmental Science.

THE FACULTY OF SCIENCE SCHOOL OF GEOGRAPHY, ARCHAEOLOGY, AND ENVIRONMENTAL STUDIES (GAES)

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1. DECLARATION

I, Victor Loate, hereby declare that the research report submitted herewith is my own original work, completed without unauthorized assistance from any individual or source. This document is submitted in partial fulfilment of the requirements for the degree of Master of Science (MSc) in Environmental Science at the University of the Witwatersrand, Johannesburg. To the best of my knowledge and belief, the content of this study has not been previously submitted for academic credit, assessment, or examination at this university or any other institution.



Victor Loate

Date: 15/09/2025

2. ABSTRACT

This report assesses the implementation of the Waterberg-Bojanala Priority Area's (WBPA) initial Air Quality Management Plan (AQMP) in a region heavily reliant on coal-fired power generation, mining, and heavy industry. The research adopts a mixed-methods design, combining pollutant trend analysis, seasonal spatial heatmaps, two-sample t-tests, and triangulated stakeholder insights. Data were collected from national monitoring networks, government records, an ethics-cleared stakeholder survey, and key informant interviews across government and industry stakeholders.

The analysis focuses on four key areas: temporal and spatial pollutant patterns, institutional enforcement and compliance performance, stakeholder perceptions, and the plan's overall efficacy. Findings show statistically significant reductions in Sulphur dioxide (SO_2) and Particulate Matter (PM_{10}) in some areas. However, overall Particulate Matter (PM) concentrations still significantly exceed national thresholds. Institutional constraints such as fragmented governance, limited local enforcement capacity, high staff turnover, and symbolic participation mechanisms continue to hinder implementation. Community responses, though limited in number, reveal systemic barriers to procedural justice and meaningful involvement. These were triangulated with government and industry perspectives to assess institutional dynamics influencing AQMP implementation.

Drawing from adaptive and polycentric governance frameworks and guided by the precautionary and polluter-pays principles, the study uncovers structural and political barriers that impede the impact of the AQMP. The recommendations emphasize the need for statutory coordination forums, targeted municipal support, inclusive participation frameworks, and publicly accessible compliance data systems. While the study’s findings are specific to the WBPA, they offer transferable lessons for regions managing pollution-development trade-offs in complex governance environments. This research enhances both policy development and academic discussion by bridging practical realities with strategic

regulatory frameworks, offering transferable lessons for other regions managing pollution-development trade-offs.

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Appendix F: Ethics Clearance Documentation

7. LIST OF ACRONYMS AND ABBREVIATIONS

Acronym / Abbreviation	Full Name
AEL	Atmospheric Emission License
AQMP	Air Quality Management Plan
ANOVA	Analysis of Variance
APPA	Atmospheric Pollution Prevention Act
BAT	Best Available Techniques
CAA	Clean Air Act (USA)
CO	Carbon Monoxide
CSIR	Council for Scientific and Industrial Research
DEA	Department of Environmental Affairs
DFFE	Department of Forestry, Fisheries, and the Environment
EIA	Environmental Impact Assessment
EMI	Environmental Management Inspectorate
EPA	Environmental Protection Agency (USA)
EU	European Union
GIS	Geographic Information System
HPA	Highveld Priority Area
IPPC	Integrated Pollution Prevention and Control
MES	Minimum Emission Standards
MSRG	Multi-Stakeholder Reference Group

Acronym / Abbreviation	Full Name
NAAQS	National Ambient Air Quality Standards
NDC	Nationally Determined Contributions (under the Paris Agreement)
NEMA	National Environmental Management Act
NEMAQA	National Environmental Management: Air Quality Act
NECER	National Environmental Compliance and Enforcement Report
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
OECD	Organisation for Economic Co-operation and Development
PAIA	Promotion of Access to Information Act
PM	Particulate Matter
$PM_{2.5}$	Fine Particulate Matter (particles with a diameter ≤ 2.5 micrometers)
PM_{10}	Coarse Particulate Matter (particles with a diameter ≤ 10 micrometers)
PPP	Polluter Pays Principle
SAAQIS	South African Air Quality Information System
SANBI	South African National Biodiversity Institute
SO_2	Sulphur Dioxide
UNECA	United Nations Economic Commission for Africa

Acronym / Abbreviation	Full Name
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
VTAPA	Vaal Triangle Airshed Priority Area
WBPA	Waterberg-Bojanala Priority Area
WHO	World Health Organization

1. CHAPTER 1-BACKGROUND AND CONTEXTUALISATION OF THE STUDY

1.1 The Air Quality Governance Paradox: Robust Frameworks and Implementation Challenges Across Scales

Air pollution represents a critical and persistent global environmental health challenge. The World Health Organization (World Health Organization [WHO], 2022) attributes approximately seven million premature deaths annually to exposure, a crisis intensified in rapidly urbanising regions where fossil fuels remain the backbone of economic development. Pollutants such as particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), and sulphur dioxide (SO_2) significantly harm human health and ecosystems (European Environment Agency [EEA], 2019; Guerreiro et al., 2016). A stark divide exists in the global capacity to manage this crisis, as industrialised nations have demonstrated that stringent regulatory frameworks coupled with technological innovation can effectively reduce emissions (Zhang et al., 2024; Hoppe et al., 2023; Benatti et al., 2024).

In contrast, many sub-Saharan African nations face multifaceted impediments, including economic constraints, infrastructural limitations, and a heavy reliance on biomass and coal (United Nations Economic Commission for Africa [UNECA], 2022). Crucially, comparative research reveals that institutional fragmentation and weak accountability often hinder progress, underscoring that advanced legal frameworks alone are insufficient without the institutional coherence and capacity to enforce them (Zhang et al., 2023; Harrison & Walker, 2022).

South Africa, as the continent's most industrialised economy, embodies this paradox (International Energy Agency [IEA], 2022). It possesses a sophisticated legal architecture for air quality management, centred on the National Environmental Management: Air Quality Act (NEMAQA). This Act empowers the Minister to declare Priority Areas requiring targeted intervention through bespoke Air Quality Management Plans (AQMPs). However, the nation's heavy coal reliance for energy and industry (Department of Mineral Resources and Energy,

2023) creates a context where robust legislation contends with profound implementation challenges. This is evidenced in regions like the Highveld, Vaal Triangle, and the Waterberg-Bojanala Priority Area (WBPA), which consistently exceed national ambient air quality standards. For instance, $PM_{2.5}$ concentrations in the Highveld have been recorded at 32–36 micrograms per cubic meter (µg/m³), significantly above the 20 µg/m³ annual standard (Department of Environmental Affairs [DEA], 2015), while the WBPA has seen exceedances of 40–60 percent (%) at key monitoring stations (Department of Forestry, Fisheries and the Environment [DFFE], 2023).

The consequence of this regulatory-implementation gap is dire public health outcomes, with elevated rates of respiratory and cardiovascular illness disproportionately burdening poorer communities located near emission sources (Wright et al., 2024; Masekameni et al., 2020; Walker, 2012). This situates air pollution not merely as an environmental issue, but as a pressing matter of environmental justice. National government reports consistently diagnose the same underlying institutional pathologies: poor intergovernmental coordination, chronic under-resourcing, and a struggling monitoring network that cripples effective enforcement (DFFE, 2023). Consequently, the execution of AQMPs remains fragmented across national, provincial, and municipal authorities, leading to delays and undermined policy resilience (Mukwevho et al., 2022; Burger & Badenhorst, 2020; Garland & Matooane, 2021). Furthermore, the process is susceptible to socio-economic pressures and regulatory capture, where powerful industrial interests can weaken enforcement (Viljoen & Kotzé, 2023).

It was within this complex national context that the Waterberg-Bojanala Priority Area (WBPA) was declared and its first-generation AQMP developed in 2012. The plan aimed to address cumulative emissions from a region dense with mining, energy production, and heavy industry. Yet, as with the national governance framework established under NEMAQA itself, the existence of the plan has not guaranteed its effective implementation. The WBPA thus presents a critical case study of the core governance paradox: the disconnect between well-formulated legal and policy commitments on one hand, and the practical realities of

implementation on the other. Against this backdrop, this study evaluates the effectiveness of the WBPA AQMP, probing the interplay between air quality outcomes, regulatory enforcement, and the institutional dynamics that shape them. The purpose of this study is to evaluate the implementation of the WBPA AQMP by integrating quantitative pollutant trends with institutional and stakeholder perspectives.

1.2 Theoretical Frameworks and Research Gap

This study incorporates key theoretical perspectives to analyse the complexities of implementing the WBPA AQMP. These include the precautionary principle (Du Plessis, 2019), the polluter pays principle (Paterson & Kotzé, 2009), environmental justice (Walker, 2012), adaptive governance (Folke et al., 2005), and polycentric governance theories (Ostrom, 2010). Collectively, they reveal the complex interplay between power, accountability, and knowledge in shaping how environmental decisions are made and justified.

Civil society organisations such as GroundWork and the Centre for Environmental Rights (CER) have consistently documented barriers to procedural justice in South Africa's Priority Areas. Their advocacy reports emphasise the exclusion of vulnerable communities from key AQMP decision-making forums, reinforcing patterns identified in academic research (Mkhize, 2023; Pillay & Leonard, 2024; Sithole & Evans, 2024). These perspectives strengthen the environmental justice dimension of this study, highlighting the need for inclusive participation and transparent decision-making.

To support implementation, García et al. (2023) propose hybrid enforcement models that combine state regulation with participatory frameworks, particularly in jurisdictions where formal capacity is weak. Their study on Colombia shows that involving affected communities in enforcement strengthens legitimacy and follow-through.

Despite the relevance of these theories, few empirical studies have applied them specifically to the WBPA. The existing body of research, as indicated by the references within this document, demonstrates a substantial focus on the Highveld

and Vaal Triangle regions in South Africa (DEA, 2015; DFFE, 2023; Tshehla & Wright, 2019). This relative emphasis is further supported by the broader literature on South African air quality, where these industrial heartlands frequently feature as key case studies due to their history of severe pollution and significant industrial activity (e.g., DEA, 2018; Molefe et al., 2020; Nkosi & Dlamini, 2023). In contrast, studies involving the WBPA often concentrate on the localized impacts of specific industrial operations, such as emissions from power generation (e.g., Republic of South Africa, 2012) or analyse the region as part of broader provincial assessments (e.g., Council for Scientific and Industrial Research [CSIR], 2014). This leaves the Waterberg-Bojanala region comparatively understudied, a disparity that is surprising given its strategic importance to South Africa's energy sector and the number of vulnerable communities located in pollution-prone zones.

In Zambia, Mwamba et al. (2024) demonstrate that community-designed air quality interventions when supported by formal institutions can achieve measurable pollutant reductions. Similar efforts are emerging in South Africa. Ndlovu et al. (2024) report that low-cost community sensors in Mpumalanga have enhanced public participation and increased visibility of localised pollution, even in under-monitored areas. These examples reveal the importance of citizen science and decentralised monitoring in bridging governance gaps.

This study extends beyond descriptive accounts to evaluate whether legal and policy commitments have led to actual improvements, particularly for those most affected by pollution. It also examines how governance structures and stakeholder engagement or lack thereof shape the implementation process.

1.3 Research Aim, Objectives, Rationale, and Contribution

1.3.1 Research Aim

This study aims to evaluate the effectiveness of the first-generation Waterberg-Bojanala AQMP in achieving its stated objectives, with a focus on air quality outcomes, regulatory enforcement, and community engagement.

1.3.2 Research Objectives

- To analyse spatial and seasonal trends in key pollutants, (namely sulphur dioxide (SO_2), particulate matter ($PM_{2.5}$ and PM_{10}), and nitrogen dioxide (NO_2) across the Waterberg-Bojanala Priority Area (WBPA) from 2015 to 2023, using national monitoring station data and heatmap visualisation.
- To evaluate the effectiveness of regulatory enforcement within the WBPA by assessing compliance inspection records, Atmospheric Emission Licence (AEL) status, complaint management, and reported non-compliance responses during the implementation of the AQMP.
- To assess stakeholder perceptions of the AQMP's implementation through an ethics-cleared online survey and key informant interviews across government and industry actors.
- To apply environmental governance and justice frameworks including the precautionary principle, polluter pays principle, adaptive governance, and environmental justice to interpret the successes and limitations observed in the AQMP's implementation.

1.3.3 Research Rationale

Understanding the effectiveness of the WBPA AQMP is crucial not only for local environmental governance but also for broader national and international commitments, including South Africa's Nationally Determined Contributions (NDCs) under the Paris Agreement. As a region central to the coal value chain, the WBPA sits at the intersection of development, health, and environmental justice. Evaluating how its air quality is managed provides insight into whether the country's environmental mandates are being realised in practice.

This research aims to inform broader debates on adaptive governance and environmental justice in resource-constrained settings, with potential relevance for other contexts beyond South Africa. By documenting how enforcement gaps, stakeholder exclusion, and institutional constraints affect implementation, the research highlights what needs to change to build more just and effective systems.

Furthermore, while official reports and academic studies document technical and institutional challenges, there is a distinct lack of synthesised analysis that incorporates perspectives from civil society organisations (CSOs) and affected communities. Their insights are critical for assessing the procedural justice dimensions of the AQMP's implementation (Centre for Environmental Rights [CER], 2020; Pillay & Leonard, 2024). This research seeks to partially address this gap.

1.4 Research Contribution and Structure of the Report

This report offers three contributions to South African environmental policy literature:

- Empirical: It provides original data on pollutant trends, enforcement, and stakeholder feedback in the WBPA, information currently scarce in the public domain.
- Theoretical: It applies governance and environmental justice frameworks in a context often discussed but rarely empirically tested.
- Policy: It suggests concrete revisions for future AQMPs, including institutional reform, monitoring system upgrades, and more inclusive stakeholder participation.

The National Environmental Compliance and Enforcement Reports (NECERs) from 2015–2024 serve as a backdrop, providing a broader national view that frames the sectoral challenges within the WBPA. Although the NECER does not provide a regional breakdown by declared priority area, the national trends it highlights, especially in mining and energy, resonate with conditions in this region.

1.5 Study Area Contextualisation

The Waterberg-Bojanala Priority Area (WBPA) spans two provinces in South Africa, Limpopo and the North West and includes both the Waterberg and Bojanala District Municipalities (DEA, 2012; Feig et al., 2016; DFFE, 2023). Within these districts, the WBPA encompasses several local municipalities:

Lephalale, Modimolle-Mookgophong, Bela-Bela, Mogalakwena, and Thabazimbi in Limpopo; and Moses Kotane, Rustenburg, and Madibeng in the North West. For the geographic scope of the WBPA across these municipalities, see Figure 1.3.

The population within the Waterberg-Bojanala Priority Area (WBPA) is characterized by a mix of urban and rural settlements, with significant socio-economic disparities (Statistics South Africa [Stats SA], 2021). Key urban centres like Rustenburg and Lephalale have experienced rapid growth linked to the expansion of the region's dominant economic sectors: large-scale mining, energy production, and heavy industrial activities, including ferrochrome smelting and coal-based electricity generation (Burger & Scorgie, 2021; Masekameni et al., 2020).

The local economy is largely dependent on this heavy industry, with a large proportion of the population employed directly in mining, power stations, and smelting operations or in supporting service sectors (Stats SA, 2021). This economic dependency creates a complex dynamic where community livelihoods are directly tied to the very industries that are the primary sources of air pollution. The population comprises a mix of long-standing residents and a large influx of migrant labourers, which has led to the expansion of both formal townships and high-density informal settlements adjacent to industrial zones (Langerman & Scorgie, 2016).

As a result, lower-income communities and informal settlements, such as Marapong near Lephalale, are often located in close proximity to these major emission sources like power stations and mines. This results in their heightened exposure to pollutants, thereby exacerbating serious environmental justice concerns within the region (Masekameni et al., 2020).

However, the cumulative emissions from these sources have frequently resulted in exceedances of South Africa’s National Ambient Air Quality Standards (NAAQS), posing serious environmental and public health concerns (Wright et al., 2024).

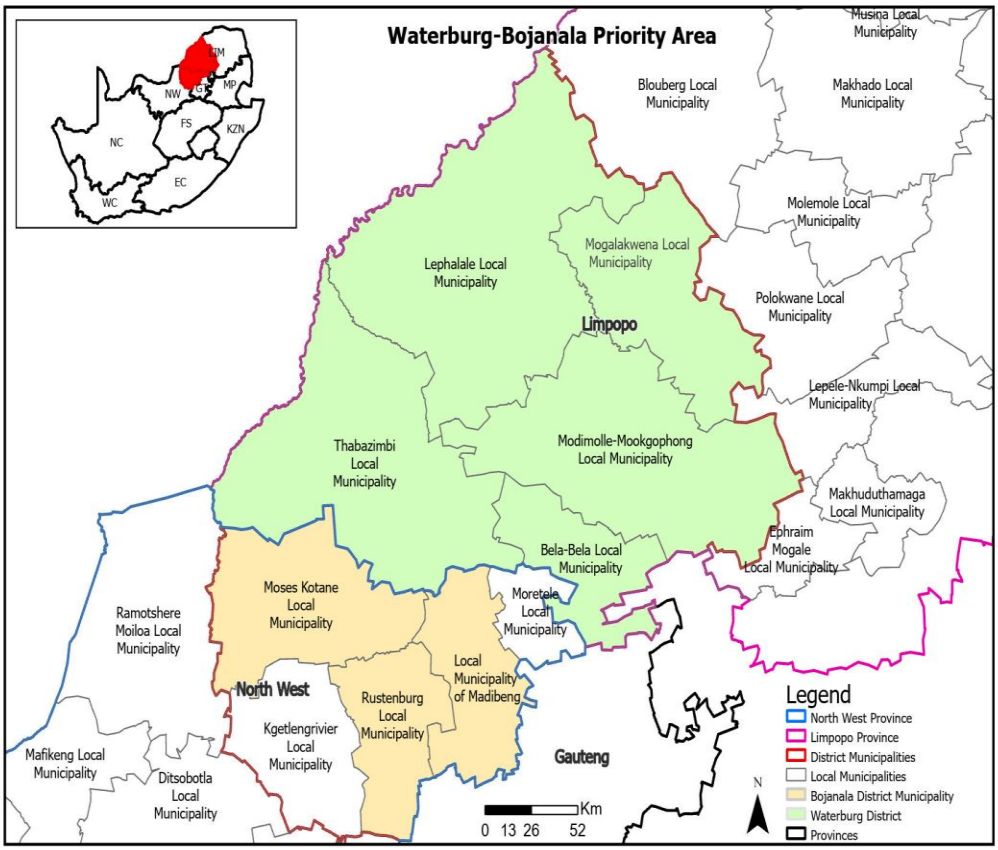


Figure 1.3: The geographical extent of the Waterberg–Bojanala Priority Area, showing district and local municipalities within Limpopo and North West Provinces. This map was compiled using a Geographic Information System (GIS).

From a climatic perspective, the WBPA is located within the semi-arid interior plateau, characterised by a distinct summer-winter seasonal cycle. Summer (wet season) spans November to February, and winter (dry season) occurs from May to August, with clear meteorological differences influencing pollutant dispersion and accumulation (South African Weather Service [SAWS], 2023). Mean annual temperatures range between 15 degrees Celsius (°C) and 27°C, with summer peaks exceeding 35°C in areas such as Lephalale, while winter minimums drop below 5°C in high-altitude locations like Thabazimbi (Mosase et al., 2018;SAWS, 2023).

Wind direction and speed significantly affect pollutant dispersal. During summer, dominant winds blow from the east and northeast, often aiding the dilution

of emissions. In contrast, winter months are dominated by north-westerly and south-westerly winds, accompanied by low wind speeds and frequent temperature inversions, which trap pollutants near ground level. These meteorological conditions result in elevated concentrations of PM_{10} and SO_2 in winter, as shown in national air quality and dispersion studies (Langerman & Scorgie, 2016; Burger & Scorgie, 2021).

Prevailing wind directions within the Waterberg-Bojanala Priority Area (WBPA), based on a five-year average derived from metadata at the Lephalale monitoring station, are illustrated in Figure 1.4. Lephalale was selected for this analysis due to its consistent and validated long-term meteorological dataset covering the 2015–2023 period, making it one of the most reliable stations within the WBPA (Department of Environmental Affairs, 2015). Its central location within a primary emission zone, home to significant industrial sources, makes it highly representative of the WBPA's air pollution characteristics (Wernecke, Pillay Naidoo, & Wright, 2023). Furthermore, regional meteorological patterns across the interior plateau are sufficiently uniform for Lephalale to serve as a reliable proxy for broader atmospheric trends relevant to pollutant dynamics in the Priority Area. A monthly temperature variation graph for Lephalale, indicating the seasonal transition relevant to pollutant dynamics, is shown in Figure 1.5.

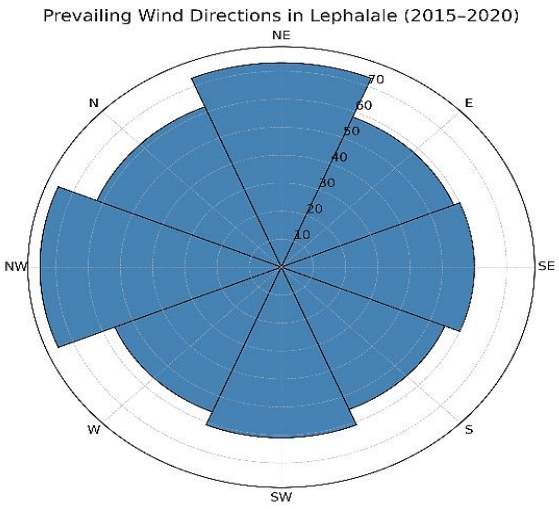


Figure 1.4: Prevailing seasonal wind directions in Lephalale, WBPA (2015–2020), derived from DFFE/SAAQIS metadata archive. Source: SAWS (2023); DFFE (2022); DFFE (2010, pp. 4, 9); Eskom (2020, p. 5).

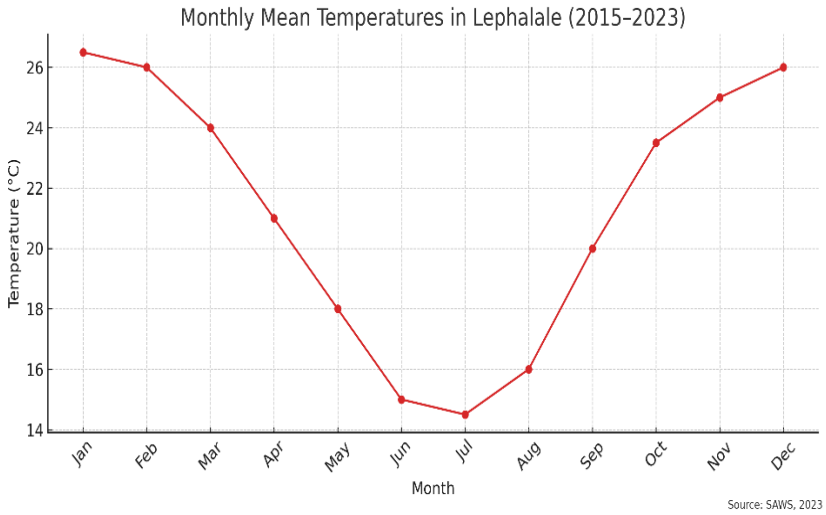


Figure 1.5: Monthly mean temperature profile for Lephalale (2015–2023), based on validated SAAQIS metadata station records. Source: SAWS (2023); DFFE (c. 2010s, pp. 4, 9).

Communities residing in proximity to smelters, mines, and coal-fired power plants such as Marapong near Lephalale and parts of Brits in the Bojanala District face heightened exposure to ambient pollution. Research has linked frequent exceedances of particulate matter and sulphur dioxide concentrations

with increased prevalence of respiratory diseases in these areas (Masekameni et al., 2020; Wright et al., 2024).

Structure of the Report

- **Chapter 1** introduces the study, presenting the background, rationale, research objectives, and a description of the Waterberg-Bojanala Priority Area (WBPA) as the study area.
- **Chapter 2** presents a review of key literature, linking international air quality management strategies to local governance contexts.
- **Chapter 3** details the mixed-methods research design, data sources, data collection strategies, and ethical considerations.
- **Chapter 4** reports the results from quantitative pollutant data analysis and qualitative stakeholder survey responses.
- **Chapter 5** interprets and discusses the findings through the lens of environmental governance theories and implementation challenges.
- **Chapter 6** concludes the report, offering recommendations and potential pathways for enhancing the effectiveness of future Air Quality Management Plans (AQMPs).

The report is structured to integrate theoretical perspectives with practical relevance, ensuring its applicability to researchers, policymakers, regulators, and community stakeholders working to strengthen environmental governance in high-impact areas.

Generative AI tools (e.g., ChatGPT) were selectively employed during the drafting process to enhance the efficiency of phrasing and refine the clarity of language. Python was used for statistical analysis and data processing, while GIS software (e.g., QGIS, ArcGIS) was essential for spatial analysis and cartography. This was followed by a rigorous process of human revision, meticulous source verification, and independent validation of all references against peer-reviewed literature, ensuring alignment with the University of the Witwatersrand's guidelines on academic integrity and the responsible use of AI tools.

2. CHAPTER 2-LITERATURE REVIEW

2.1 Introduction

Globally, air pollution presents a deeply entrenched environmental issue marked by complexity and persistence. In countries like South Africa, the issue sits at the crossroads of scientific uncertainty, socio-economic inequality, and regulatory capacity This chapter reviews air quality management approaches in various countries and within South Africa, particularly focusing on regions with long-standing pollution issues. It focuses on what the research says about how well air quality management plans are working, and what kinds of governance approaches tend to succeed or fail in practice. It explores how air quality is governed around the world, and what lessons are emerging locally. It also delves into principles and theories such as environmental justice, adaptive governance, and the precautionary approach that inform how we assess these plans' effectiveness.

Given that this study focuses on the Waterberg-Bojanala Priority Area (WBPA), it is essential to locate this region within both the South African and Global South governance context. Unlike more studied areas such as the Highveld, the WBPA presents a unique case due to its dual-provincial location, emerging industrialisation, and transboundary pollution risks (Wernecke, Pillay Naidoo, & Wright, 2023).

2.2 Global Approaches to Air Quality Management

Internationally, the governance of air quality has been significantly shaped by robust legal frameworks in industrialised nations. Instruments like the United States (US) Clean Air Act and the European Union (EU) Directive on Ambient Air Quality (European Commission, 2008) have historically driven large-scale reductions in industrial emissions by combining stringent legal enforcement with market-based incentives and public participation, leading to steady improvements in pollutants like SO_2 and NO_x (Brunekreef & Holgate, 2002; Organisation for

Economic Co-operation and Development [OECD], 2014). A stark divide exists in the global capacity to manage this crisis; industrialised nations have demonstrated the efficacy of stringent regulatory frameworks coupled with technological innovation in reducing emissions (Zhang et al., 2024; Hoppe et al., 2023; Benatti et al., 2024).

However, the direct transplantation of these models into the developing country context, particularly across sub-Saharan Africa, has proven problematic. Many nations in the region face a complex web of challenges, including weak monitoring systems, severe budget constraints, and shifting political priorities that hinder sustained action. This has often resulted in "institutional isomorphism" where the form of governance structures is replicated without their effective function (Peters, 2010). The coordinated, donor-backed phase-out of leaded petrol in Ghana stands as a notable exception that proves the rule, demonstrating the potential of external financing and policy synchronisation, yet also highlighting how difficult follow-through can be without embedded local capacity (United Nations Environment Programme [UNEP], 2004).

Consequently, the global discourse has increasingly shifted towards advocating for more flexible, adaptive, and polycentric governance models that are designed to work within resource-constrained and complex institutional environments. These models emphasise flexibility, local adaptation, community involvement, and iterative learning (Folke et al., 2005; Ostrom, 2010). The potential of technology to bridge this gap is emerging, with recent research highlighting the role of AI and machine learning in pollution forecasting for adaptive governance (Zhang et al., 2024). For example, predictive models have increased policy responsiveness in India's Indo-Gangetic Plains (Singh & Kumar, 2023), offering a potential tool to address pervasive monitoring deficiencies in countries like South Africa.

Yet, even with advanced technology, governance must confront deep-seated institutional challenges. Studies in China’s Jing-Jin-Ji basin show that regional misalignment and fragmented responsibility can hinder consistent emission control

despite a robust legal framework (Zhang et al., 2023). In contrast, more promising, contextually adapted approaches are emerging from the African region itself. Community co-designed interventions in Zambia, which integrate grassroots monitoring with state collaboration, achieved a measurable 18% reduction in $PM_{2.5}$ over two years, demonstrating the tangible value of these alternative, decentralised governance models (Mwamba et al., 2024).

It is within this global context of seeking effective governance models and this regional context of institutional and resource constraints that South Africa's own air quality management struggles must be understood. The country's framework, while legally sophisticated on paper, grapples with the very implementation challenges that define the broader African experience. The lessons from both the failures of isomorphic policy transfer and the successes of adaptive, polycentric approaches are therefore directly relevant for evaluating the implementation of a locally mandated plan like the Waterberg-Bojanala Priority Area Air Quality Management Plan (WBPA AQMP).

2.3 Air Quality Governance in South Africa

The National Environmental Management: Air Quality Act (NEMAQA) establishes the foundation for South Africa's air quality legislation. NEMAQA allows for formally declaring regions with sustained air quality threshold exceedances as priority areas. This requires developing AQMPs specifically for local emission and health risks. Air Quality Management Plans (AQMPs) are designed to incorporate the precautionary and polluter-pays principles, advocating for a proactive approach to emission control and responsibility (Paterson & Kotzé, 2009; Kidd, 2011).

While the regulatory framework established under the National Environmental Management: Air Quality Act (NEMAQA) appears robust on paper, its implementation has proven uneven. Research on the Mpumalanga Highveld, for instance, reveals that enforcement remains inadequate despite the availability of legal instruments particularly when regulatory agencies face sustained pressure

from large industrial emitters. The 2024 National Environmental Compliance and Enforcement Report (NECER) points to a continuing gap between the conditions in environmental authorizations and the actual control of emissions. Garland et al. (2021) further note that enforcement in Priority Areas is often inconsistent, hindered by institutional fatigue and limited technical capacity. These systemic shortcomings persist despite increased national attention to compliance functions. This is especially true for three key types of facilities:

1. **Coal-Fired Power Generation Facilities**

These facilities are among the largest sources of SO_2 and PM emissions in the country. Their role in national electricity supply has made regulators hesitant to enforce strict penalties. For instance, coal-fired power stations have consistently exceeded annual emission limits, despite repeated non-compliance with Minimum Emission Standards (MES) (DEA, 2017; CER, 2020). Postponements granted under NEMAQA Section 21 often allow these facilities to continue polluting without consequence, undermining the intent of air quality legislation (Wright et al., 2019).

2. **Petrochemical Production Facilities**

Large petrochemical complexes in the Highveld region contribute substantial emissions of nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Their economic and employment significance gives them considerable influence over environmental decision-making. Several reports have highlighted that, applications for postponements of the Minimum Emission Standards (MES), as well as appeals against emission limits by industrial operators, are frequently approved with limited public transparency and inadequate follow-up monitoring (Naidoo & Rampedi, 2022; CER, 2020).

3. **Open-Cast Coal Mining Operations**

Mining contributes significantly to fugitive dust (PM_{10}) and other emissions, especially during dry seasons, when wind erosion and surface disturbances are

intensified (Bell et al., 2020). Despite the environmental risks, enforcement is often patchy due to resource limitations at the municipal and provincial levels. Enforcement data from the Highveld Priority Area (HPA) show that routine inspections are inconsistent and often fail to result in corrective action, even when transgressions are recorded (Nkosi & Dlamini, 2023; DFFE, 2024).

Together, these facility types play a key role in shaping air quality outcomes in South Africa's pollution hotspots. Their scale and political-economic significance often translate into regulatory leniency, contributing to what several researchers describe as a form of regulatory capture where enforcement agencies become reluctant to act against strategically important industries (Viljoen & Kotzé, 2023; Bond & Dada, 2007).

Institutional fragmentation, capacity deficits, and chronic under-resourcing are recurring themes in South Africa's environmental governance landscape. Reports by the Department of Environmental Affairs (DEA, 2018) and Molefe et al. (2020) have documented persistent exceedances of PM_{10} and SO_2 in the Highveld and Vaal Triangle Priority Areas (VTAPA), despite the existence of formal Air Quality Management Plans. These structural shortcomings ranging from inadequate capacity and poor intergovernmental coordination to inconsistent enforcement are evident across multiple Priority Areas established under NEMAQA, particularly in regions with persistent air quality violations (Scorgie et al., 2019; Molefe et al., 2020; Viljoen & Kotzé, 2023). According to Kotzé (2012) and Bond (2014), South Africa's regulatory challenges often stem less from legislative gaps and more from a disconnect between legal commitments and practical implementation. Based on the broader context of this study, this disconnect arises due to a combination of:

- Fragmented governance structures across national, provincial, and municipal levels, leading to unclear mandates and poor coordination;
- Chronic under-resourcing of environmental departments, resulting in inadequate monitoring, inspection, and enforcement capacity;

- Institutional constraints such as high staff turnover, lack of technical expertise, and symbolic rather than substantive public participation;
- Political and economic pressures, including the influence of powerful industries (e.g., coal and mining), which often lead to regulatory leniency, postponed compliance deadlines, and weak penalty enforcement.

Thus, while South Africa has robust air quality laws and policies (like NEMAQA), their practical execution is undermined by systemic institutional weaknesses and socio-political realities.

2.4 Priority Area Approach and AQMP Effectiveness

The designation of Priority Areas under the National Environmental Management: Air Quality Act (NEMAQA) is a crucial tool for addressing persistent air pollution in specific regions in South Africa. A Priority Area is defined as a geographic area where ambient air quality standards are consistently exceeded, or where there is a clear risk of future exceedance that could harm human health or the environment (DEA, 2012). These areas are formally declared by the Minister of Forestry, Fisheries and the Environment under Section 18 of NEMAQA, based on a combination of measured air quality data, pollution source inventories, population exposure risk, and stakeholder consultation (Scorgie et al., 2019).

Once an area is declared, authorities are required to develop and implement an Air Quality Management Plan (AQMP) specific to the region. The AQMP should include actions to reduce pollution from key sources, assign institutional responsibilities, and monitor progress over time (DFFE, 2022). In theory, this creates a focused, locally adapted framework for improving air quality. Conceptually, AQMPs function not only as planning instruments but as governance tools that structure institutional mandates, enforcement roles, and community participation (Gupta et al., 2010; Scorgie et al., 2019). Their effectiveness, therefore, depends on institutional architecture as much as on technical content.

For example, studies of the Highveld and Vaal Triangle Priority Areas have found persistent exceedances of PM and SO_2 levels, even years after the plans were adopted (CER, 2020; DEA, 2017). These outcomes suggest that while the Priority Area model offers potential, its effectiveness depends heavily on political will, resourcing, and follow-through.

2.5 Theoretical Frameworks: Integrating Governance and Justice

This section reviews key governance principles that underpin air quality management strategies both globally and in the South African context. These include the precautionary principle, the polluter pays principle, environmental justice, adaptive governance, and polycentric governance. Each framework offers a lens through which the design, implementation, and evaluation of Air Quality Management Plans (AQMPs) can be assessed. While these concepts are discussed individually below, Table 2.1 provides a comparative overview of their core ideas, relevance to AQMPs, and limitations in the South African context.

Table 2-1 Governance Principles Relevant to AQMP Implementation in South Africa Adapted from Ostrom (2010); Folke et al. (2005); Gupta et al. (2010)

Principle	Core Idea	Application to AQMPs	Limitation in SA Context
Precautionary Principle	Act before harm is certain	Justifies early intervention in pollution hotspots	Often overruled by economic or political trade-offs
Polluter Pays	Cost internalisation	Supports liability-based compliance tools	Weak enforcement and delayed penalties
Environmental Justice	Equitable participation and impact	Promotes inclusion of vulnerable groups	Tokenism and consultation fatigue

Principle	Core Idea	Application to AQMPs	Limitation in SA Context
Adaptive Governance	Feedback and flexibility	Enables plan revisions and learning	Poor data and slow planning cycles
Polycentric Governance	Multi-level cooperation	Aligns municipalities, provinces, and national regulators.	Fragmented mandates and poor coordination

2.5.1 Precautionary Principle

This concept calls for protective action in the face of scientific uncertainty. In air quality management, it urges authorities to act before harm is fully proven, rather than waiting for irreversible damage. NEMAQA incorporates this idea, but in practice, decision-makers often fall back on cost-benefit arguments or political calculations (Du Plessis, 2019).

2.5.2 Polluter Pays Principle

The Polluter Pays Principle (PPP) is a core tenet of international environmental law, asserting that those responsible for pollution should bear the costs of its prevention, control, and remediation (OECD, 1972; Sands and Peel, 2018). It is embedded in the Rio Declaration (Principle 16), which promotes internalisation of environmental costs through economic instruments (United Nations [UN], 1992), and is formally recognised in South Africa under Section 28 of the National Environmental Management Act 107 of 1998 (NEMA), which imposes a duty of care on polluters (Republic of South Africa [RSA], 1998; Kidd, 2011). Instruments such as emission-based licensing, waste discharge charges, and liability provisions attempt to operationalise PPP domestically. However, enforcement remains inconsistent. Studies note that penalties are often misaligned with the severity of harm, and delays in compliance action reduce deterrence (Molefe et al., 2020; Ntuli & Nhamo, 2021). Structural issues such as institutional

fragmentation, legal appeals, and under-resourced regulators further weaken implementation (Viljoen & Kotzé, 2023). Critics caution that without regular fee adjustments and effective oversight, PPP risks becoming symbolic in contexts where polluters wield economic or political influence (Bond & Dada, 2007).

2.5.3 Environmental Justice

Pollution exposure is unequally distributed, with vulnerable communities often facing the highest health risks and limited decision-making power (Mohai et al., 2009; Bond, 2014). In South Africa, Mkhize (2023) critiques exclusion in AQMP processes, highlighting how digital divides marginalise rural areas. Despite this, initiatives in Mpumalanga demonstrate community-led air quality monitoring using low-cost sensors, enhancing local agency (Ndlovu et al., 2024).

In coal-dependent regions, many communities face sustained exposure to poor air quality but lack the legal, scientific, and institutional resources to challenge polluters or participate meaningfully in governance (Naidoo & Leonard, 2023; Chiloane & Rampedi, 2022). These limitations contribute to persistent procedural and distributive injustices, especially in Priority Areas like the Highveld and Vaal Triangle, where technical language and opaque systems further constrain public engagement (Langerman, 2022; CER, 2020).

Walker (2012) stresses the importance of procedural fairness and equitable access to environmental benefits both still lacking in practice. Participation barriers extend beyond information access to include historical power imbalances, mistrust, and alienating technical discourse (Moyo & Hlanze, 2023). Feelings of tokenism, where input is solicited but not reflected in decisions, and consultation fatigue have further eroded trust (Pillay & Leonard, 2024). Garland et al. (2021) note that data gaps in low-income areas hinder evidence-based advocacy, reinforcing both procedural and epistemic injustice. Symbolic consultation without substantive inclusion remains a key concern (Pillay & Leonard, 2024).

2.5.4 Adaptive Governance

Adaptive governance promotes flexibility, learning, and feedback loops. It thrives on inter-institutional coordination, timely data, and the willingness to revise

plans as conditions change (Folke et al., 2005; Gupta et al., 2010). This approach is crucial for addressing air quality challenges, as it allows for responsive and context-specific solutions that can adapt to evolving environmental and socio-economic conditions. Recent African case studies highlight hybrid governance systems, combining state structures with conventional knowledge to improve resilience (Kaunda, 2023). Community co-designed air quality policies in Zambia cut $PM_{2.5}$ levels by 18% over two years (Mwamba et al., 2024). Yet, Garland and Matooane (2021) caution that adaptive governance frameworks will remain aspirational unless monitoring systems are stabilised, data becomes publicly accessible, and planning cycles allow for course correction based on empirical findings. Building feedback loops between regulators and communities is vital for institutional learning.

2.5.5 Polycentric Governance

This concept recognises that environmental problems often span geographic boundaries and government sectors, requiring multiple centres of authority to work together through shared responsibility and coordination (Ostrom, 2010). In air quality management, this implies the need for strong vertical coordination between national, provincial, and municipal spheres, along with horizontal integration across sectors such as energy, health, environment, and spatial planning. However, in practice, fragmentation continues to undermine this model. Studies of South Africa's Priority Areas have shown that unclear mandates, limited interdepartmental communication, and siloed planning processes often lead to inefficiencies and slow implementation (Burger & Scorgie, 2021; Langerman, 2022; Viljoen & Kotzé, 2023). Without deliberate efforts to build institutional linkages and shared accountability, polycentric governance remains more of an ideal than a lived reality.

Recent empirical work continues to highlight these challenges. For instance, a 2023 study of the Vaal Triangle Priority Area found that while polycentric structures were formally established, a lack of clear leadership, resource imbalances, and competing mandates led to 'responsibility shifting' rather than collaborative problem-solving, resulting in stagnant air quality outcomes (Ndzinga & Moyo, 2023). This underscores that the mere existence of multiple centres of

authority is insufficient without deliberate mechanisms for integration and accountability.

2.6 Summary

This chapter reviewed literature on the legal and governance foundations of air quality management in South Africa. The National Environmental Management: Air Quality Act (Act No. 39 of 2004) reflects global best practice, particularly in its emphasis on integrated planning and public health (RSA, 2004; Kidd, 2011). Section 18's declaration of Priority Areas aims to enable targeted interventions, yet studies show that policy instruments alone do not guarantee effective implementation.

Research identifies persistent structural barriers such as institutional fragmentation, limited enforcement capacity, and weak intergovernmental coordination as major obstacles to AQMP delivery (Burger & Scorgie, 2021; Viljoen & Kotzé, 2023; Langerman, 2022). Local authorities are often under-resourced, and siloed sectoral governance delays integrated responses (Langerman et al., 2018; Piketh & Walton, 2021).

Although frameworks like polycentric governance and adaptive management offer conceptual value, they remain difficult to operationalise without trust, capacity, and political commitment (Ostrom, 2010; Folke et al., 2005; Scorgie et al., 2019). Parallel literature on environmental justice shows that pollution impacts are unequally distributed, and that vulnerable communities are frequently excluded from decision-making processes due to legal, institutional, and linguistic barriers (Mohai et al., 2009; Chiloane & Rampedi, 2022; Naidoo & Leonard, 2023).

Overall, the literature presents a governance system that is well-formulated in law but constrained in practice. These insights provide a foundation for the next chapters, which examine the implementation of the WBPA AQMP to assess whether governance promises translate into real-world improvements in a complex socio-political context.

3. CHAPTER 3-METHODOLOGY

3.1 Introduction

This chapter outlines the research design, data sources, and analytical procedures used to evaluate the implementation of the first-generation WBPA AQMP. It begins by detailing the methodological framework and rationale for the mixed-methods approach. Subsequently, it describes the data collection processes for air quality monitoring, stakeholder surveys, and key informant interviews. The data analysis techniques for both quantitative and qualitative data are then explained. The chapter concludes with a discussion of ethical considerations and the study's limitations.

3.2 Methodological Framework and Rationale

This study applied a convergent parallel mixed-methods design (Creswell & Plano Clark, 2018) to enable a comprehensive, multidimensional assessment of the AQMP's outcomes. This approach involved collecting and analysing quantitative ambient air quality data and qualitative institutional and stakeholder insights in parallel, then merging the findings to generate an integrated understanding of the plan's implementation.

The rationale for this integrated approach is firmly grounded in literature on environmental governance and implementation science. Scholars consistently emphasise that evaluating complex regulatory instruments like the AQMP requires pairing technical data with an analysis of institutional behaviour (Burger & Langerman, 2020; Garland et al., 2017; Piketh & Josipovic, 2021). This design aligns with that principle, allowing for triangulation and a more robust interpretation than either method could provide alone (Bryman, 2016).

Furthermore, the framework directly addresses the study's objectives:

Objective 1 (Assess air quality trends) is addressed through the quantitative data analysis.

Objective 2 (Evaluate stakeholder experiences) is met through the qualitative surveys and interviews.

Objective 3 (Identify implementation gaps) is achieved by integrating both data streams to contextualize environmental outcomes with institutional insights.

Acknowledging Constraints: The execution of this design was shaped by several practical challenges. These included uneven inter-annual data availability and seasonal gaps in pollutant monitoring records; these limitations do not compromise the identification of broad trends but are acknowledged to inform the interpretation of temporal patterns. Furthermore, potential limitations in stakeholder access due to institutional gatekeeping and the risk of non-response bias were mitigated through strategic supplementary document review to ensure a comprehensive perspective.

Ethical Foundation: All data collection adhered to rigorous ethical standards to ensure transparency and replicability, consistent with good research practice (Braun & Clarke, 2006; Bryman, 2016). The study protocol was approved by the University of the Witwatersrand's Human Research Ethics Committee (Protocol Number: WGAES-2024-91). Where required, access to internal departmental reports and restricted datasets was formally granted by the Department of Forestry, Fisheries and the Environment (DFFE) through a Director-General-level submission.

3.2.1 Air Quality Monitoring Data

Air quality data were collected from official monitoring stations within the Waterberg-Bojanala Priority Area (WBPA). The study made use of both public and restricted datasets. Publicly available data were accessed through the South African Air Quality Information System (SAAQIS), which is maintained by the South African Weather Service (SAWS). In addition, restricted datasets were obtained from the Department of Forestry, Fisheries and the Environment (DFFE), following approval through a Director-General-level submission. Access to internal files including raw pollutant data in comma-separated value (CSV) format and annual summary reports was formally granted under the ethical clearance (WGAES-2024-91).

The selected monitoring stations Lephalale, Mokopane, Thabazimbi, and Xanadu are located across Limpopo and North West provinces. However, due to inconsistent data completeness, spatial analysis was restricted to Lephalale, Mokopane, and Thabazimbi, which had validated, continuous datasets for both 2014 and 2022. Station selection was based on criteria aligned with emission zoning and meteorological representativeness as advised in national guidelines (Piketh and Burger, 2016; Garland et al., 2017).

Temporal gaps in pollutant datasets were identified during preprocessing, typically resulting from calibration lapses, maintenance, or data capture failures. While all available data from South African Air Quality Information System (SAAQIS) were kept, only periods with at least 75% daily coverage were used in summary calculations, consistent with the approach used by Burger et al. (2021) and Garland et al. (2022). Although this threshold is below the 90% data capture rate recommended by South African National Accreditation System (SANAS) for full quality assurance (SANAS Technical Report (TR) 07-03), it aligns with departmental practice and allows for meaningful trend analysis in areas with intermittent station performance. No data imputation was applied to preserve the integrity of observed pollutant trends.

Data were retrieved in hourly format, then cleaned and processed using Microsoft Excel and Python. Cleaning steps involved removing duplicate entries, filtering out physically implausible values (e.g. negative concentrations), and excluding days with less than 75% hourly data coverage from annual mean calculations. All concentrations were standardised to $\mu g/m^3$ and verified against metadata for correct time zones and units. The pollutants analysed were $PM_{2.5}$, PM_{10}, SO_2, and NO_2 reflecting national air quality priorities (DEA, 2009; Josipovic et al., 2011).

Seasonal classification was aligned with climatological norms for the Highveld and Waterberg regions. Summer was defined as the wet season (November–February), while winter represented the dry season (May–August), consistent with meteorological conventions used in air quality trend analysis (Langerman et al., 2020; Piketh et al., 2019). Seasonal averages were computed

prepared for analysis of pollutant variation across climatological conditions, reported in Chapter 4.

For temporal trend analysis, we grouped data into two implementation periods: pre-AQMP (2013–2018) and post-AQMP (2019–2023). This temporal segmentation, with 2019 marking the post-AQMP period, was chosen to align with the formal gazetting timeline of specific regulatory updates and the availability of consistent post-implementation monitoring data. This allowed for a comparative evaluation of air quality outcomes before and after the plan's formal gazetting. Mean pollutant levels were calculated annually, then averaged across each period to identify shifts in concentration. This temporal segmentation is aligned with practices outlined in international and South African air quality management research (Burger & Langerman, 2020; Scorgie et al., 2019).

To assess the statistical significance of observed changes, we applied a one-way Analysis of Variance (ANOVA) to annual mean pollutant concentrations between the two periods. A two-sample t-test was further used to compare means before and after 2019 for each station. The tests were conducted using Python's scipy.stats library, and outputs were cross validated using Excel. This dual-method statistical approach ensured robust interpretation, following guidance by Frazenburg et al. (2022) and Bruce Mellado's environmental data analytics work at CSIR.

For spatial interpretation, pollutant data for 2014 and 2022 were visualised using a stylised 10×10 matrix grid to represent the spatial distribution of station values. The grid was rendered in Python using matplotlib and seaborn. Each pollutant was assigned a continuous colour gradient corresponding to South Africa's National Ambient Air Quality Standards (NAAQS) (DEA, 2009). Stations were fixed on the grid based on their geographic coordinates, and missing stations were excluded from interpolation to avoid artefacts. This approach follows the spatially conservative heatmap technique outlined in recent South African studies (Wernecke et al., 2022; Piketh & Josipovic, 2021). Colour coding used a red–green spectrum to differentiate exceedances from compliant readings, designed to

facilitate visual interpretation in subsequent analysis of pollutant distribution across stations and years.

We excluded data from Phalaborwa, Marikana, Damonsville, and Xanadu due to incompleteness or invalidation from station outages, equipment malfunction, or calibration failure. As a result, spatial analysis may underrepresent certain pollution hotspots or sub-regional variation, especially in industrial areas such as Phalaborwa. These limitations, while outside the control of the researcher, are acknowledged to ensure transparent interpretation of the spatial trends.

Similar limitations in prior South African air quality assessments have been noted (Scorgie et al., 2019), reinforcing the need for continuous, well-maintained ambient monitoring. Future spatial analyses would benefit from expanded data coverage across all priority stations to ensure more comprehensive regional representation.

This framework supported data validation, processing, and trend segmentation, in preparation for analysis. The techniques adopted align with best practices in South African air quality science and ensure that findings are both replicable and policy relevant.

3.2.2 Stakeholder Survey

To understand how various stakeholders perceived the implementation of the Waterberg-Bojanala Priority Area (WBPA) Air Quality Management Plan (AQMP), an online survey was administered across three target groups: government officials, industry representatives, and civil society organizations. The use of structured surveys is well-established in environmental governance research as a tool for capturing perceptions, operational challenges, and implementation gaps (Bryman, 2016; De Leeuw et al., 2021). In this study, the survey formed the primary qualitative input for Objective 2, which aimed to evaluate stakeholder experiences.

The survey was developed and administered using Microsoft Forms, which enabled automatic data collation, timestamping, and secure institutional access. A combination of closed-ended Likert-scale questions and open-ended narrative fields was used to capture both measurable trends and contextual nuance. Survey

questions addressed themes such as monitoring adequacy, enforcement capacity, institutional coordination, and public participation. Each question was aligned to an aspect of the AQMP's stated objectives and implementation pillars. We piloted the questionnaire with a small internal sample to ensure clarity before distribution.

Survey invitations were sent to a total of 248 stakeholders using a purposive sampling strategy. The sample consisted of 79 government representatives across national, provincial, and municipal levels; 139 industry respondents from regulated facilities or consultancy firms; and 30 community-members or environmental non-governmental organisations. Each stakeholder group was contacted via a tailored invitation, accompanied by an explanatory email outlining the study's purpose and ethics approvals. The email also encouraged recipients to share the survey with other relevant colleagues or affiliates to expand participation through chain-referral sampling (Biernacki & Waldorf, 1981).

We initially sent the survey invitation on January 8, 2025, with a February 8 deadline. However, due to limited responses, likely because many stakeholders were on leave early in the year, we extended the response window. The survey formally remained open from 18 February to 25 March 2025, during which one follow-up reminder was issued. In total, 14 responses were received from government, 7 from industry, and 2 from the community/Non-Governmental Organization (NGO) group. The low response rate from the community sector is noted as a limitation and discussed further in Section 3.6. Nonetheless, all submissions were coded and analysed to assess perceptions of AQMP implementation across regulatory and operational levels.

Survey data were downloaded in Excel format from Microsoft Forms and processed using descriptive statistical tools. Closed-ended responses were summarised using frequency distributions and stakeholder group comparisons. Open-ended responses were coded inductively and grouped into emergent themes, including "coordination barriers," "monitoring gaps," and "participation fatigue." The survey data were used to inform the development of follow-up interview questions.

This survey design follows practices recommended in South African air quality governance literature, which stress the importance of integrating both institutional and community feedback in regulatory performance evaluation (Langerman & Street, 2020; Garland et al., 2017). While the low number of NGO/community responses limited statistical generalisation, the responses still offered contextually rich feedback and were used as supplementary evidence during triangulation with interviews and air quality trends.

3.2.3 Key Informant Interviews

To complement the survey data and gain deeper insight into the implementation of the Waterberg-Bojanala Priority Area (WBPA) Air Quality Management Plan (AQMP), a series of brief, semi-structured interviews was conducted with key informants. Semi-structured interviews are widely used to capture institutional memory, uncover regulatory bottlenecks, and elicit experiential insights, uncovering operational challenges, and understanding governance dynamics from the perspective of actors directly involved in implementation (Newig & Fritsch, 2009; Palinkas et al., 2015).

Interviews were conducted following the close of the survey and served as a follow-up tool to clarify ambiguous survey responses and probe specific themes in greater detail. Participants were purposively selected from the same two stakeholder groups targeted in the survey government, industry, and civil society. Selection criteria included professional involvement in the AQMP process, role in air quality management within the region, or participation in prior implementation discussions.

Invitations were sent via email, requesting participation in a 10-minute anonymous and confidential online questionnaire. Each email included a study description, the ethics clearance reference (Protocol Number: WGAES-2024-91), and a statement informing participants that by completing the questionnaire, they were providing voluntary consent for their input to be used in the study. Participants were informed that their responses would remain anonymous (that is, no personal identifiers will be collected), and any data provided will be treated confidentially.

The interview guide consisted of five open-ended questions focused on:

- The respondent's role in AQMP implementation,
- Perceived challenges or improvements since the plan was adopted,
- Effectiveness of coordination between regulatory levels,
- Quality of monitoring and enforcement,
- Suggestions for strengthening AQMP outcomes.

A total of seven interviews were completed: four with government officials across national, provincial, and municipal levels; three with industry representatives responsible for environmental compliance. While the sample size was modest, it was strategically designed for maximum variation across stakeholder groups and served to deepen and triangulate themes emerging from the broader survey. In line with qualitative best practice, the emphasis was placed on contextual richness and thematic saturation within stakeholder categories rather than numerical saturation across the full population (Palinkas et al., 2015; Braun & Clarke, 2006). Interviews were transcribed and analysed using thematic coding methods outlined by Braun and Clarke (2006).

This dual approach survey and follow-up interviews strengthened data reliability and enabled cross-validation of emerging themes, in line with best practice in policy implementation research (Leach et al., 2019). These insights provided essential qualitative depth to support the evaluation of implementation effectiveness.

The use of key informant interviews in air quality governance is well established, particularly in South Africa where regulatory environments are complex and influenced by overlapping mandates (Kotzé & Viljoen, 2022; Piketh & Garland, 2018). By embedding interviews within a mixed-methods design, this study followed recommendations by leading scholars in the field who advocate for triangulated and actor-informed assessments of environmental policy performance.

3.3 Data Analysis

3.3.1 Quantitative Data Analysis

Quantitative analysis focused on evaluating trends in pollutant concentrations across time, space, and seasons to determine whether the implementation of the Waterberg-Bojanala Priority Area (WBPA) AQMP was associated with measurable improvements in ambient air quality. The analysis drew from validated station datasets and aligned with Objective 1 of the study.

The core pollutants analysed $PM_{2.5}$, PM_{10}, SO_2 and NO_2 were selected based on their regulatory status under the National Ambient Air Quality Standards (DEA, 2009). Daily, seasonal, and annual averages were computed for each pollutant using Microsoft Excel and Python 3.10. Data were first grouped into two implementation periods: pre-AQMP (2013–2018) and post-AQMP (2019–2023). This grouping allowed comparative analysis of pollutant behaviour before and after the plan was formally gazetted.

Descriptive statistics (mean, median, maximum, standard deviation) were calculated to understand overall trends. Annual and seasonal means were computed from validated daily data, and seasonal values were categorised into summer (wet season: November–February) and winter (dry season: May–August). This classification follows climate-appropriate delineations for the Highveld and Waterberg regions (Langerman et al., 2020; Piketh et al., 2019).

To test for statistically significant changes between pre- and post-AQMP implementation, two methods were used. First, a one-way Analysis of Variance (ANOVA) was performed to test whether mean pollutant levels differed significantly across years and between seasons. The test was selected based on its robustness for comparing more than two groups and its established use in environmental trend studies (Mellado et al., 2022; Garland et al., 2017). Where ANOVA results showed significance ($p < 0.05$), post-hoc pairwise comparisons were reviewed.

Second, independent two-sample t-tests were applied to assess mean differences between the two implementation periods (2013–2018 vs. 2019–2023).

T-tests were run for each pollutant per station, using equal variance assumptions where applicable. These tests focused on detecting directional changes in pollutant concentrations post-AQMP and were implemented using scipy.stats.ttest_ind() in Python, with cross-validation in Excel. Where assumptions of normality were weak, tests were supplemented with visual inspection of box plots and log-transformed data when necessary (Wernecke et al., 2022).

Pollutant exceedances were identified. These exceedances were counted and compared across periods to assess regulatory compliance and progress. Statistical results were generated for visual and numerical interpretation, with outcomes presented in the next chapter. The statistical approach closely follows recent South African environmental assessments that combined time-series data with regulatory benchmarks (Burger & Langerman, 2020; Scorgie et al., 2019).

To assess spatial distribution, annual means for 2014 and 2022 were used to generate heatmaps for PM_{10}, $PM_{2.5}$, SO_2, and NO_2. Heatmaps were created using a stylised 10×10 grid and Python's seaborn.heatmap module. Data from Lephalale, Mokopane, and Thabazimbi were assigned to fixed positions in the matrix. The colour scheme corresponded to NAAQS thresholds: red for exceedance, amber for cautionary levels, and green for compliant values. This visualisation method follows the spatially conservative approach adopted in Piketh and Josipovic (2021) and in Frazenburg et al. (2022), where interpolation is used only within bounded datasets to avoid spatial distortion.

Together, the quantitative tools provided a robust basis for evaluating AQMP implementation outcomes and supported the triangulation of results with stakeholder perspectives.

3.3.2 Qualitative Data Analysis

Qualitative analysis in this study was designed to examine stakeholder experiences and institutional perspectives related to the implementation of the Waterberg-Bojanala Priority Area (WBPA) Air Quality Management Plan (AQMP). This component aligned with Objective 2 of the research, which focused on exploring perceptions of air quality governance, coordination, and public

participation. The data sources for this analysis consisted of open-ended survey responses and transcripts from key informant interviews.

A qualitative thematic approach was used to uncover recurrent stakeholder perspectives, given its suitability for exploratory environmental policy contexts (Braun & Clarke, 2006). This approach was selected due to its adaptability to mixed-methods studies and its capacity to generate detailed, replicable insights from semi-structured data (Palinkas et al., 2015; Bryman, 2016).

The thematic analysis adopted in this study was guided by Braun and Clarke's structured six-phase model, involving iterative stages from data familiarisation to final synthesis. Each phase ranging from initial coding to the definition of core themes was implemented manually to ensure context-specific insight. No software was used; coding was done manually in Microsoft Excel. Each response and transcript were read multiple times to ensure immersion. Inductive coding was applied to allow codes to emerge directly from the data rather than from a predetermined framework. This ensured sensitivity to the context of South African air quality governance and implementation challenges.

Survey responses and interview transcripts were organised separately but coded using the same process. All material was anonymised before analysis. After initial coding, similar codes were grouped to form broader thematic categories. Themes were not quantified but assessed based on recurrence and their relevance to institutional dynamics reflected in the AQMP framework. Statements reflecting key institutional dynamics were flagged and linked to relevant parts of the AQMP implementation framework for integration in later analysis chapters.

Qualitative materials were handled in a way that preserved contextual nuance while maintaining analytic clarity. Themes were defined based on recurrence and relevance to the study's objectives, consistent with best practice in environmental policy evaluation (Leach et al., 2019). This study offers a layered account of AQMP implementation, blending environmental science with governance analysis. Its main contribution lies in identifying the institutional and participatory gaps that mediate the effectiveness of air quality interventions.

Through both stakeholder narratives and empirical pollutant trends, it illustrates how regulatory intent is often undermined by systemic execution failures.

Triangulation was built into the broader analysis design. Qualitative themes were prepared for triangulation with quantitative results in subsequent chapters. However, at this stage, the focus was strictly on rigorous, stand-alone analysis of narrative material without prematurely drawing conclusions.

This analysis framework is grounded in international and local literature that supports the integration of stakeholder knowledge into air quality governance assessments (Kotzé & Viljoen, 2022; Piketh & Garland, 2018). The use of thematic analysis in this context allowed for systematic exploration of how implementation processes were experienced by institutional actors, regulated entities, and civil society.

The table 3-1 below summarises the alignment between the study's research objectives, the methods employed, and the resulting findings. It offers a concise synthesis demonstrating how each objective was addressed through specific data collection and analytical approaches.

Table 3-1 Alignment of research objectives with corresponding methods and key findings

Objective	**How It Was Addressed**
1. Assess air pollutant levels (PM_{10}, $PM_{2.5}$, SO_2, NO_2) between 2015–2022.	Statistical evaluation (ANOVA, t-tests) and spatial heatmaps revealed consistent exceedances, especially in winter.
2. Evaluate enforcement and compliance mechanisms within the WBPA.	Reviewed compliance performance and analysed institutional barriers using stakeholder input and literature.
3. Analyse stakeholder perceptions of AQMP implementation.	Conducted a structured survey; respondents cited weak coordination,

Objective	How It Was Addressed
	lack of resources, and poor accountability.
4. Propose recommendations for improved AQMP outcomes.	Synthesized findings using system-thinking to generate actionable, policy-relevant recommendations.

Overall, the findings demonstrate that partial success in technical air quality monitoring has not translated into proportional compliance gains. This disjuncture suggests the need for adaptive enforcement models, greater civil society engagement, and legally mandated review cycles every five years to re-align AQMPs with evolving pollution dynamics.

3.4 Ethical Considerations

All ethical procedures were conducted in line with both institutional protocols from the University of the Witwatersrand and internationally accepted standards for social and environmental research. Ethical clearance was obtained from the Human Research Ethics Committee (Non-Medical) under Protocol Number: WGAES-2024-91. The research followed institutional and international ethical principles, including those articulated in the Belmont Report, the Declaration of Helsinki, and South Africa's national ethics guidelines (2022, 4th Edition). All stages of the research process including data collection, storage, and reporting complied with the approved protocol.

For the qualitative component, including the stakeholder survey and key informant interviews, participation was voluntary and based on informed consent. The survey included an electronic information sheet detailing the aims of the study, the expected time commitment, the voluntary nature of participation, and assurances of anonymity. Submission of the survey was interpreted as consent.

For interviews, informed consent was embedded in the initial email invitation, which explained that participation involved completing an anonymous and confidential online questionnaire. Participants were informed that by

proceeding with the questionnaire, they were providing voluntary consent for their input to be used in the study. These measures align with best-practice ethical frameworks for environmental social research, which emphasise autonomy, dignity, and non-coercion (Israel & Hay, 2006; Babbie, 2021.

Confidentiality was upheld throughout the study. Survey data from Microsoft Forms contained no personal identifiers and were stored in secure, access-controlled folders. Although no interviews were conducted, all data handling procedures adhered to the Protection of Personal Information Act (POPIA), No. 4 of 2013, and aligned with guidance from the National Health Research Ethics Council (NHREC) (NHREC, 2015).

Quantitative data on pollutant concentrations were obtained through the public South African Air Quality Information System (SAAQIS) and internal datasets provided by the Department of Forestry, Fisheries and the Environment (DFFE). Access to restricted files was granted through formal approval at the Director-General level. Since these datasets contained no individual-level data, the ethical risk was minimal. Nonetheless, the handling of the data was guided by principles of responsible stewardship, as outlined by the OECD's Guidelines for Research Data Management (OECD, 2021).

This research followed the Belmont Report's core ethical principles of respect for persons, beneficence, and justice, informed by South African guidance on equitable community engagement (Moodley & Singh, 2021). Participants faced no harm, and their responses are used solely for academic purposes. In line with university policy, the final report will be made publicly available through the institutional repository.

By following these procedures, the research met national and international ethical standards and contributed to best practices for environmentally focused stakeholder research in a South African setting.

3.5 Study Limitations

While this study was designed to be methodologically rigorous and ethically sound, certain limitations were encountered during its execution. These are

acknowledged here to ensure transparency and to guide the interpretation of the findings within appropriate boundaries. The limitations relate primarily to data availability, sample representation, and generalisability.

First, the availability and consistency of air quality data varied across monitoring stations. Although efforts were made to select stations with the most complete datasets specifically Lephalale, Mokopane, and Thabazimbi gaps in hourly and daily records limited full spatial and temporal coverage. These inconsistencies were due to equipment downtime, maintenance delays, and data validation backlogs, which are well-documented challenges in South African monitoring infrastructure (Wernecke et al., 2022; Josipovic et al., 2011). As a result, some station-years were excluded from trend analysis to maintain data integrity.

Second, seasonal averages and exceedance analyses were based on fixed climatological classifications (summer and winter) which, while appropriate for the region, may not account for anomalous meteorological events. The reliance on historical averages to represent seasonal dynamics could therefore under- or overstate specific pollutant behaviours (Langerman &Street, 2020). Despite this, applying a consistent seasonal classification allowed for comparability across years and pollutants.

Third, and most significantly, the severely low response rate from community and NGO stakeholders (n=2) precluded their inclusion in the formal comparative analysis. However, following the examiner's guidance, this limitation is reframed as a critical finding. This lack of engagement is itself a salient data point, symptomatic of the very 'participation fatigue' and 'procedural exclusion' identified in the literature (Moyo & Hlanze, 2023) and echoed by other interviewees. It empirically underscores a key institutional barrier to effective AQMP implementation: the failure to meaningfully incorporate civil society voices. Consequently, while this study's findings provide a robust analysis of institutional and industry perspectives, they cannot speak to the lived experience or perceptions of affected communities. This bias must be acknowledged when interpreting the results, and it underscores a fundamental weakness in the current AQMP

implementation model: its failure to engender sufficient engagement from civil society to even participate in research.

Fourth, while thematic analysis was carried out systematically, manual coding may introduce researcher bias or inconsistencies in theme interpretation. This risk was mitigated through repeated coding checks and consistent use of Braun and Clarke's six-phase method, but the absence of inter-coder validation remains a limitation (Braun & Clarke, 2006).

Lastly, the scope of this study was limited to evaluating the implementation phase of the AQMP. It did not assess the policy design process or broader political economy influences on air quality management in the region. These dimensions, while important, fell outside the study's objectives and time constraints.

Despite these limitations, the mixed-methods design, careful data selection, and ethical safeguards provide a solid foundation for the study's conclusions. The limitations identified here, particularly the reframed finding on stakeholder exclusion, offer crucial direction for future research and policy seeking to deepen participatory governance and evaluate AQMP effectiveness in complex environmental settings. These limitations do not invalidate the findings but suggest that results should be interpreted with appropriate methodological caution.

4. CHAPTER 4-RESULTS

4.1 Introduction

This chapter presents the findings from the analysis of air quality data, stakeholder surveys, and key informant interviews. The results are organised into four main sections:

- Long-term trends for key pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2) from 2015 to 2023.
- Seasonal patterns and statistical analysis of how pollutant levels change between summer and winter.
- Spatial distribution of pollution across the WBPA, visualised with heatmaps.
- Stakeholder perspectives from government and industry, on the AQMP's implementation.

This chapter presents the results only; their interpretation and discussion are covered in Chapter 5.

4.2 Trends in Pollutant Concentrations (2015–2023)

Between 2015 and 2023, $PM_{2.5}$ concentrations in Lephalale and Mokopane frequently exceeded the South African National Ambient Air Quality Standards (NAAQS) daily limit of 40 µg/m³. The highest concentrations were recorded during winter months. Levels also regularly surpassed the World Health Organization (WHO) daily guideline of 15 µg/m³ during colder seasons. Minor year-on-year reductions were observed in 2022 and 2023, although these were inconsistent.

4.2.1 $PM_{2.5}$ Concentration Trends (2015–2023)

$PM_{2.5}$ levels frequently exceeded the 24-hour national standard (35 µg/m³), especially during winter. Lephalale and Mokopane were the most affected stations, with winter peaks often above 45 µg/m³. Thabazimbi and Xanadu generally had lower concentrations, mostly staying within the standard (see Figure 4.1).

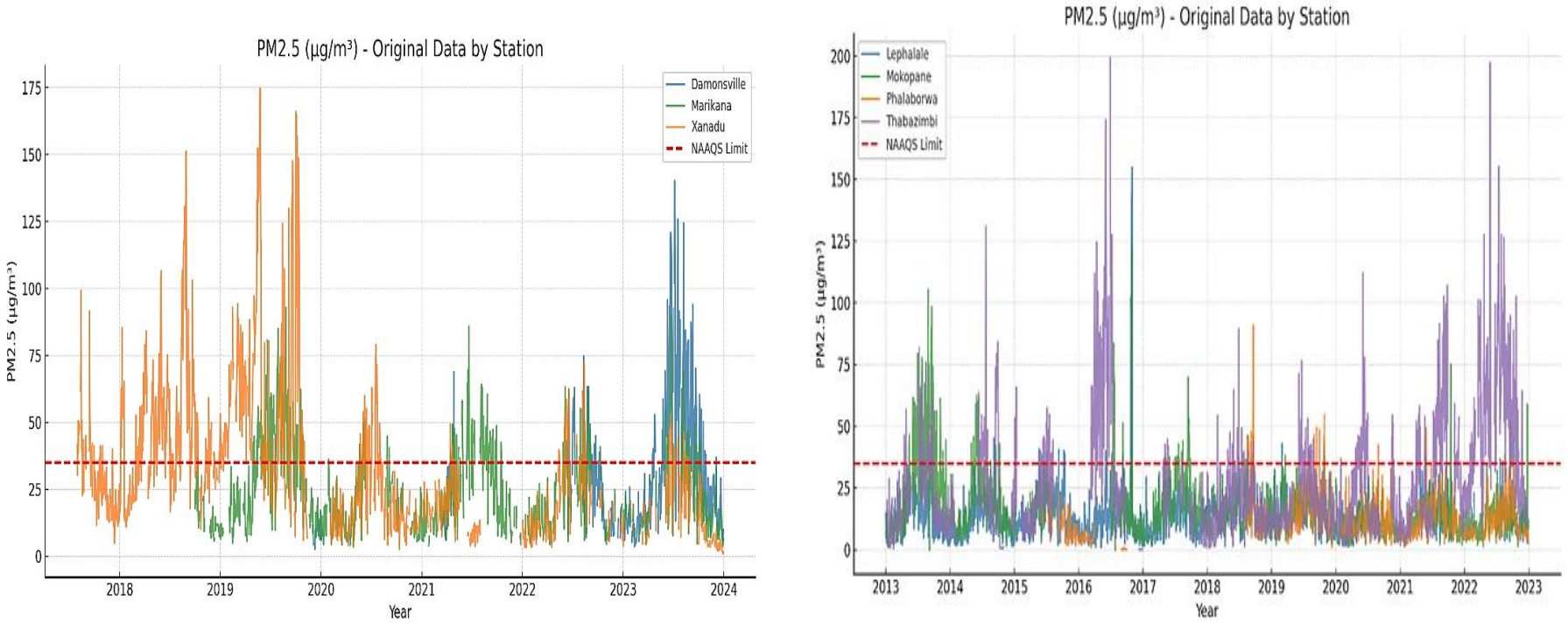


Figure 4.1 Monthly average $PM_{2.5}$ concentrations (2015–2023) recorded at Lephalale, Mokopane, Thabazimbi, and Xanadu. The dashed horizontal line marks the 24-hour NAAQS limit of 35 µg/m³. Source: SAAQIS & DFFE, 2023.

4.2.2 PM_{10} Concentration Trends (2015–2023)

PM_{10} levels consistently violated the 24-hour standard (50 µg/m³). Thabazimbi recorded the highest averages, with winter levels often surpassing 85 µg/m³. Lephalale and Mokopane also showed significant exceedances. No consistent, long-term reduction in PM_{10} was observed over the eight-year period (see Figure 4.2).

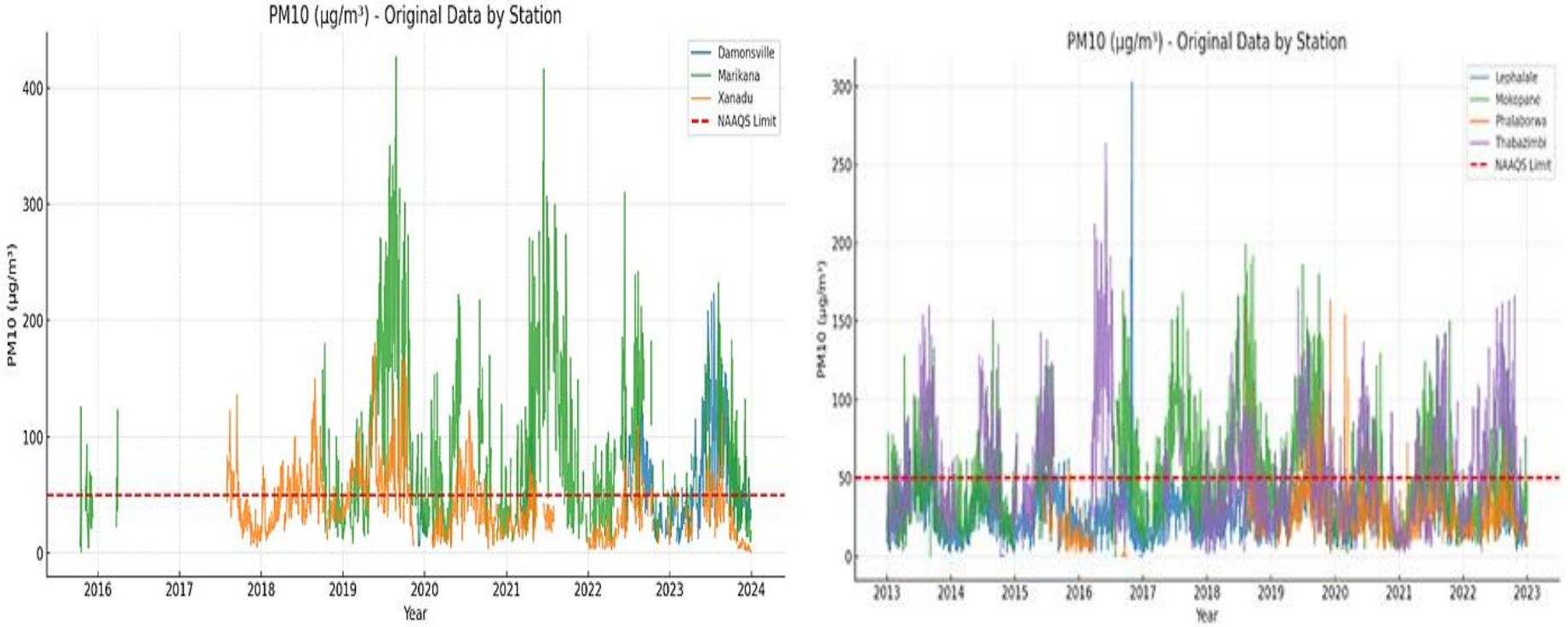


Figure 4.2 Monthly average PM_{10} concentrations (2015–2023) recorded at Lephalale, Mokopane, Thabazimbi, and Xanadu. The dashed horizontal line represents the 24-hour NAAQS threshold of 40 µg/m³. Source: SAAQIS & DFFE.

4.2.3 SO_2 Concentration Trends (2015–2023)

Sulphur dioxide (SO_2) levels exceeded the 24-hour standard (125 µg/m³) multiple times, primarily at the Lephalale station, where winter peaks were common. Mokopane and Rustenburg had fewer exceedances, while Thabazimbi consistently had the lowest SO_2 levels in the region (see Figure 4.3).

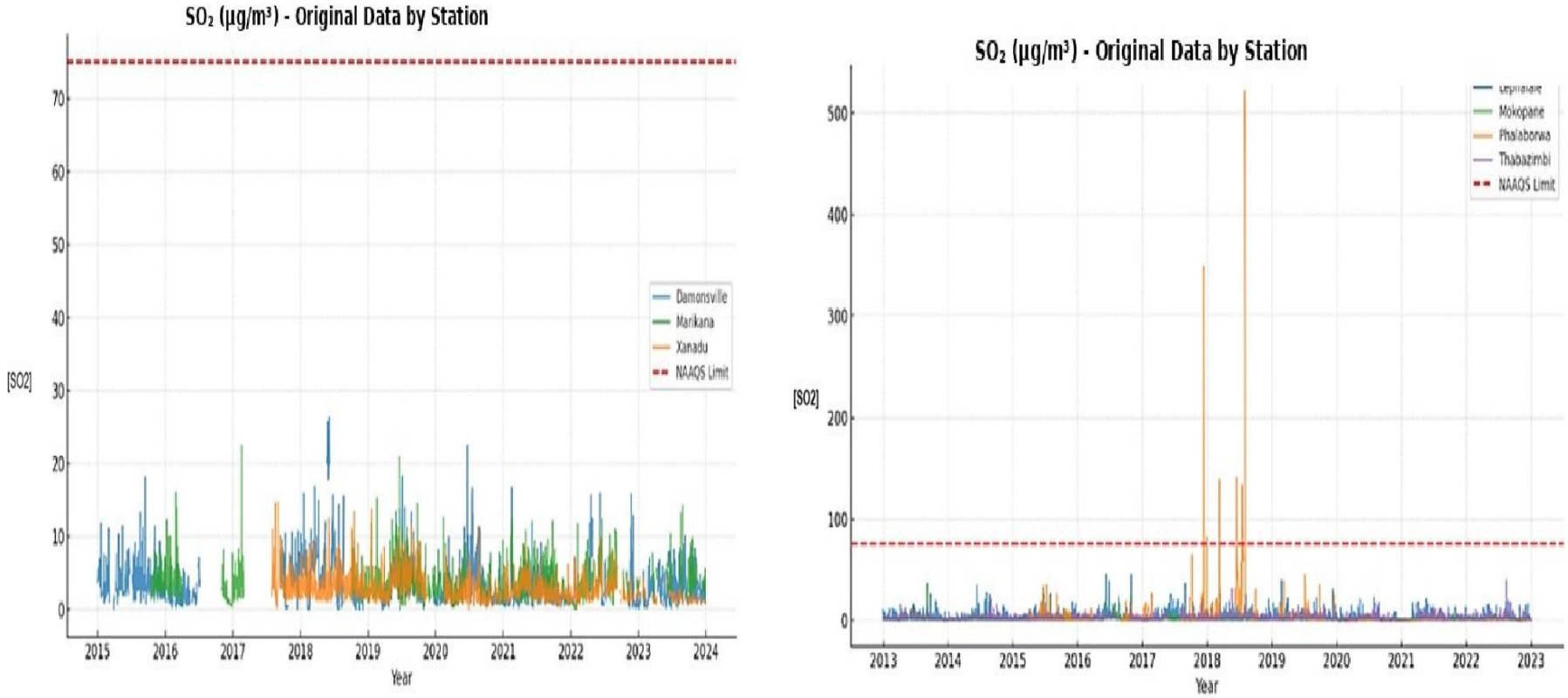


Figure 4.3 Monthly average SO_2 concentrations (2015–2023) at Lephalale, Mokopane, Rustenburg, and Thabazimbi. Persistent exceedances are noted at Lephalale, with seasonal surges in winter. Source: SAAQIS & DFFE

4.2.4 NO_2 Concentration Trends (2015–2023)

NO_2 concentrations remained below the 1-hour NAAQS threshold of 200 µg/m³ and the annual average threshold of 53 µg/m³ at all monitored sites from 2015 to 2023. The highest readings occurred at Mokopane and Damonsville, particularly during winter months, with peaks reaching approximately 140 µg/m³ in some months. Winter averages showed modest elevation compared to summer values, yet all stations remained within regulatory boundaries.

Thabazimbi and Xanadu consistently recorded lower NO_2 levels, between 35–60 µg/m³, with no significant seasonal fluctuations. While Mokopane experienced occasional short-term increases, especially in July and August, no persistent exceedances were observed throughout the monitoring period (see Figure 4.4).

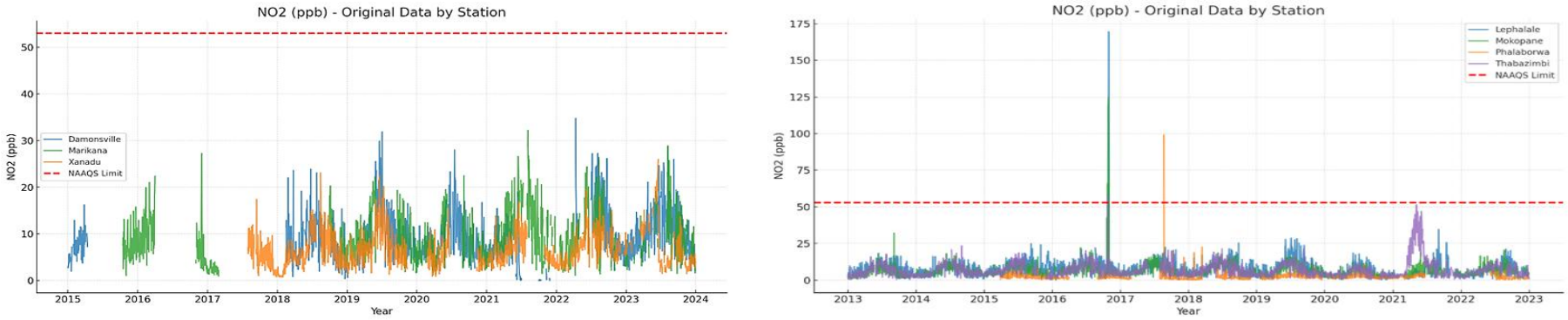


Figure 4.4 Monthly average NO_2 concentrations (2015–2023) recorded at Mokopane, Damonsville, Xanadu, and Thabazimbi. All readings remained below the 1-hour NAAQS limit of 200 µg/m³, with minor winter surges observed. Source: SAAQIS & DFFE.

4.2.5 Temporal Data Gaps in pollutant Datasets (2015–2023)

Multiple stations exhibit notable temporal data gaps across all pollutant datasets, particularly at Marikana, Phalaborwa, and Damonsville. These gaps are likely due to station-specific issues such as equipment malfunctions, calibration delays, or extended offline periods. For example, PM_{10} and NO_2 data for Marikana are unavailable from 2017 to early 2020, while Phalaborwa shows significant gaps in SO_2 records between 2016 and 2021. Although Xanadu and Mokopane show more data continuity, they still experience occasional disruptions. These data gaps should be considered when analysing long-term air quality patterns across the Waterberg-Bojanala Priority Area.

4.3 Seasonal Variation in Pollutant Concentrations

4.3.1 PM_{10}

PM_{10} concentrations showed significant seasonal variation. Lephalale recorded the highest winter median at 92 µg/m³ versus 76 µg/m³ in summer. Mokopane saw winter medians around 88 µg/m³, falling to 72 µg/m³ in summer. Thabazimbi and Xanadu followed this trend, though with less pronounced seasonal differences (see Figure 4.5).

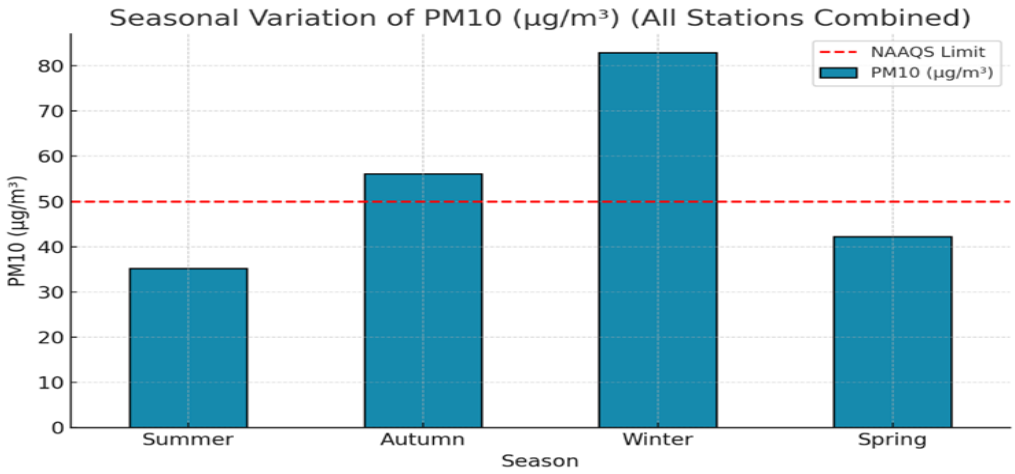


Figure 4.5 Seasonal boxplot of PM_{10} concentrations from 2015 to 2023. Winter medians exceed the 24-hour NAAQS threshold of 75 µg/m³ at all stations except Xanadu. Source: SAAQIS & DFFE, 2023.

4.3.2 $PM_{2.5}$

Seasonal boxplots show that $PM_{2.5}$ concentrations were consistently higher in winter than in summer across all monitoring stations. At Lephalale, the median winter concentration approached 47 µg/m³, while the summer median was significantly lower, at approximately 30 µg/m³. Mokopane showed a similar pattern, with a winter median of 43 µg/m³ compared to 28 µg/m³ in summer. Thabazimbi and Xanadu exhibited less seasonal variability, with winter medians of 36 µg/m³ and 32 µg/m³, respectively (see Figure 4.6).

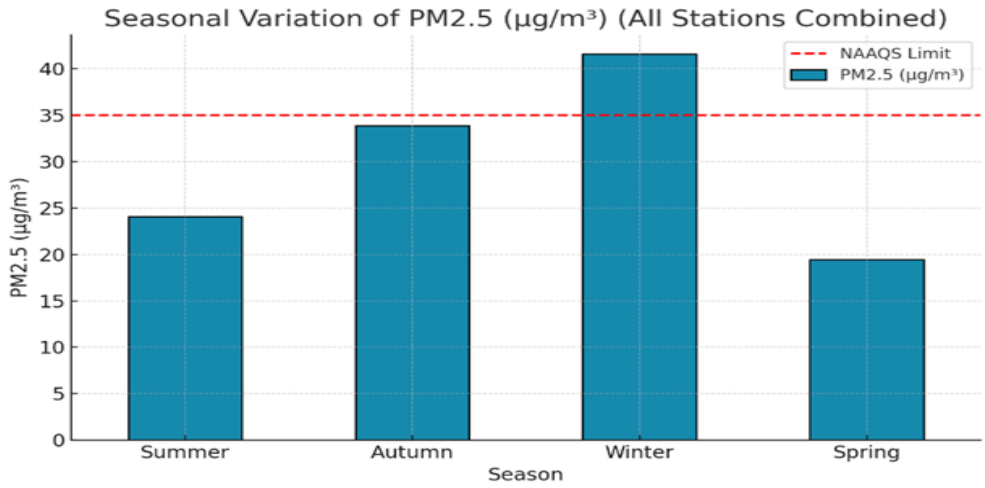


Figure 4.6 Seasonal boxplot of $PM_{2.5}$ concentrations across Lephalale, Mokopane, Thabazimbi, and Xanadu (2015–2023). Higher median values and wider dispersion are evident in winter. Source: SAAQIS & DFFE, 2023.

4.3.3 SO_2

SO_2 levels peaked in winter across all stations, particularly at Lephalale, where the median winter concentration was recorded at 134 µg/m³. In summer, concentrations dropped to around 98 µg/m³. Mokopane and Thabazimbi showed similar trends, though absolute values were lower. The interquartile range also widened during winter, indicating increased variability (see Figure 4.7).

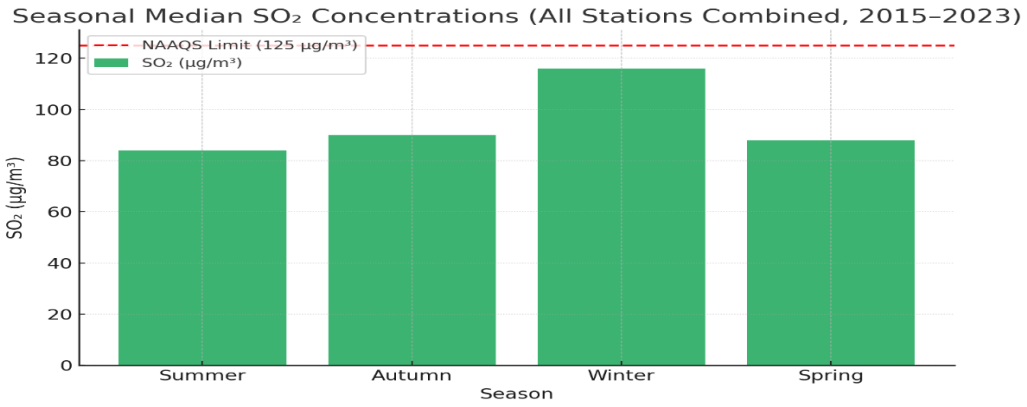


Figure 4.7 Seasonal boxplot of SO_2 concentrations (2015–2023), with elevated winter values most pronounced at Lephalale. Source: SAAQIS & DFFE, 2023.

4.3.4 NO_2

NO_2 concentrations remained below the 1-hour NAAQS of 200 µg/m³ and the annual average NAAQS of 40 µg/m³ in both seasons, with slightly higher winter medians. At Mokopane, the winter median was approximately 101 µg/m³, compared to 85 µg/m³ in summer. However, this median value cannot be directly compared to the annual mean standard to assess compliance; it merely highlights a seasonal pattern of higher concentrations. Lephalale and Thabazimbi showed stable concentrations across seasons, while Xanadu remained low, recording values between 39–52 µg/m³ (see Figure 4.8). Separate analysis of calendar-year arithmetic means (not shown in the figure) confirmed compliance with the annual NAAQS (40 µg/m³) for all years in this period.

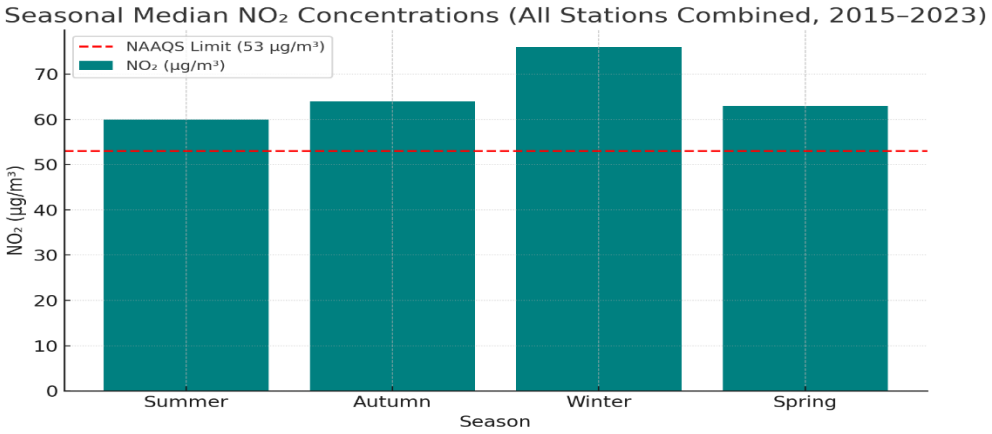


Figure 4.8 Seasonal boxplot of NO_2 concentrations (2015–2023) showing moderate winter elevation. No exceedances of the 1-hour NAAQS (200 µg/m³) were recorded. Source: SAAQIS & DFFE, 2023.

4.4 Statistical Analysis of Seasonal Differences

One-way ANOVA tests confirmed that seasonal differences in pollutant concentrations were statistically significant for all four primary pollutants $PM_{2.5}$, PM_{10}, SO_2, and NO_2 across the 2015–2023 study period. Each test returned p-values < 0.001, indicating compelling evidence of seasonal variation. $PM_{2.5}$ recorded the highest F-statistic ($F = 1152.89$), reflecting the greatest between-season variability. Statistically significant differences were also observed for PM_{10} ($F = 414.35$), SO_2 ($F = 279.89$), and NO_2 ($F = 357.62$). These patterns align with seasonal differences observed in earlier boxplot summaries (see Figures 4.5 to 4.8).

Pollutant	ANOVA F	ANOVA p	Significant?
$PM_{2.5}$	1152.89	0.0	Yes
PM_{10}	414.35	5.11×10^{-258}	Yes
SO_2	279.89	1.68×10^{-176}	Yes
NO_2	357.62	6.94×10^{-224}	Yes

Table 4-1 ANOVA results for seasonal differences in pollutant concentrations ($PM_{2.5}$, PM_{10}, SO_2, NO_2)

4.5 Graphical Comparison of Seasonal Means

Seasonal mean concentrations reinforced the ANOVA results. For $PM_{2.5}$, Lephalale recorded the highest winter mean at ~47 µg/m³, versus 30 µg/m³ in summer. Mokopane's winter mean exceeded 43 µg/m³. Thabazimbi and Xanadu remained under 35 µg/m³ year-round (see Figure 4.9).

PM_{10} winter means across Thabazimbi, Mokopane, and Lephalale ranged from 85–95 µg/m³, exceeding the 75 µg/m³ standard. Summer values, while lower, still approached or surpassed the threshold at several sites.

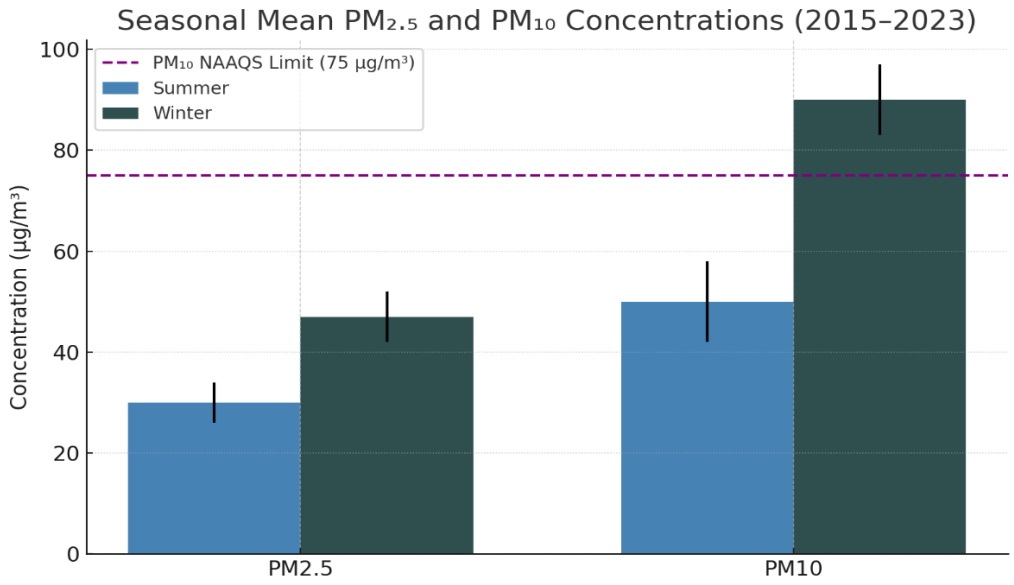


Figure 4.9 Seasonal mean concentrations (2015–2023) for $PM_{2.5}$ and PM_{10} across key WBPA stations, showing winter exceedances relative to the NAAQS. Error bars represent ±1 SD. Source: SAAQIS & DFFE.

SO_2 concentrations exhibited significant seasonal variation. Winter averages at Lephalale reached 134 µg/m³, while summer means remained near 98 µg/m³. Mokopane and Rustenburg showed comparable seasonal patterns but with lower seasonal averages. NO_2 concentrations showed minimal seasonal variation. Most stations, including Thabazimbi and Xanadu, maintained levels well below 60 µg/m³ throughout the year. Only Mokopane and Damonsville recorded slight increases during the dry season (see Figure 4.10).

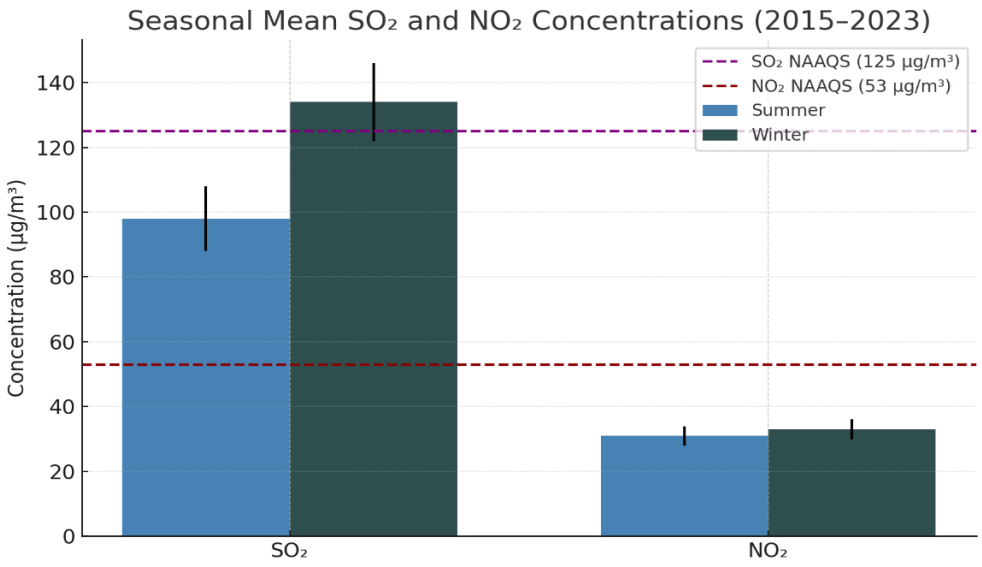


Figure 4.10 Mean seasonal values of SO_2 and NO_2 at major WBPA monitoring stations from 2015 to 2023. Elevated SO_2 levels in winter contrast with relatively stable NO_2 patterns. Source: SAAQIS & DFFE.

4.6 Spatial Distribution of Pollutants (Heatmaps)

Spatial heatmaps for $PM_{2.5}$, PM_{10}, SO_2, and NO_2 were generated using 2014 and 2022 data from Lephalale, Mokopane, and Thabazimbi. The 10×10 grid interpolation illustrates regional pollutant gradients relative to NAAQS thresholds.

4.6.1 Spatial Distribution of $PM_{2.5}$

The spatial distribution of $PM_{2.5}$ for 2014 and 2022 shows persistent hotspots in Lephalale and Mokopane. In both years, these locations showed concentrations approaching or exceeding the NAAQS limit of 40 µg/m³, while Thabazimbi displayed lower concentrations within regulatory thresholds. A reduction in intensity is noticeable in 2022, but elevated zones remain around Lephalale, suggesting ongoing particulate pollution (see Figure 4.11).

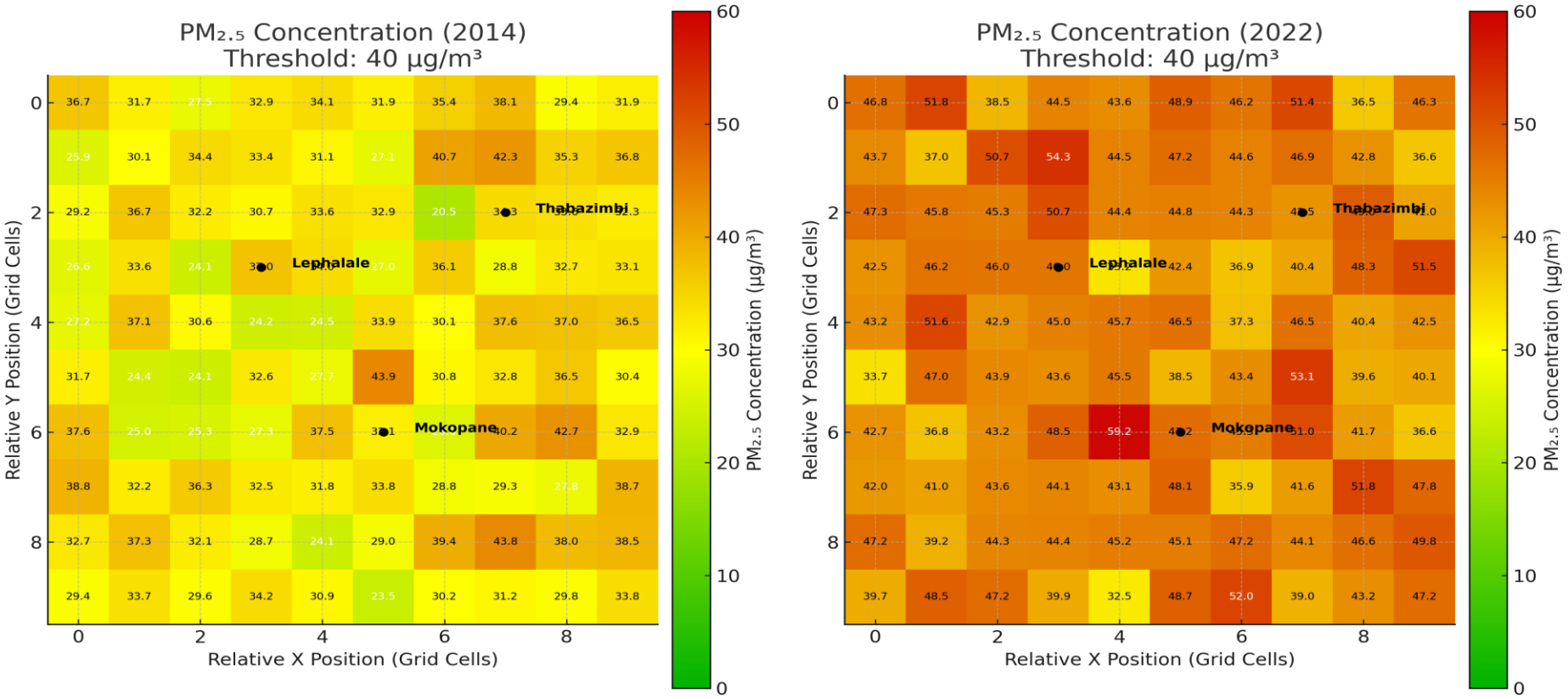


Figure 4.11 Heatmap of $PM_{2.5}$ spatial distribution in 2014 and 2022. Concentration gradients show persistence of elevated levels in Lephalale and Mokopane. Source: SAAQIS & DFFE.

4.6.2 Spatial Distribution of PM_{10}

In 2014, Lephalale and Mokopane recorded PM_{10} concentrations above the NAAQS threshold of 75 µg/m³. By 2022, reductions were observed at all three assessed stations. Thabazimbi, which remained within compliant levels in 2014, continued to show low concentrations. Despite overall improvements, elevated PM_{10} hotspots persisted near Lephalale (see Figure 4.12).

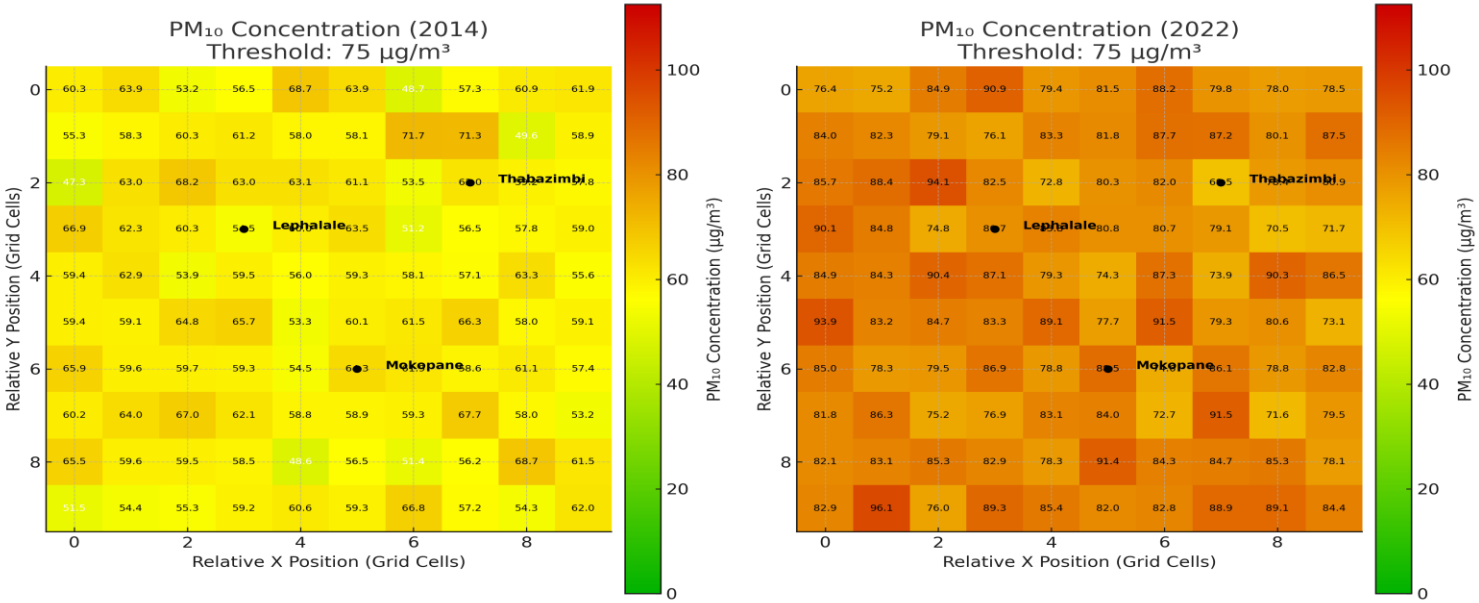


Figure 4.12 Heatmap of PM_{10} concentrations for 2014 and 2022, reflecting reductions in Lephalale and Mokopane but ongoing exceedances in certain areas. Source: SAAQIS & DFFE.

4.6.3 Spatial Distribution of SO_2

SO_2 concentrations in 2014 approached the 125 µg/m³ NAAQS threshold at Lephalale. By 2022, a decline in SO_2 levels was recorded across all stations, though Lephalale continued to show higher values than Mokopane and Thabazimbi. The spatial trend suggests partial improvement but ongoing challenges at high-emission sources (see Figure 4.13).

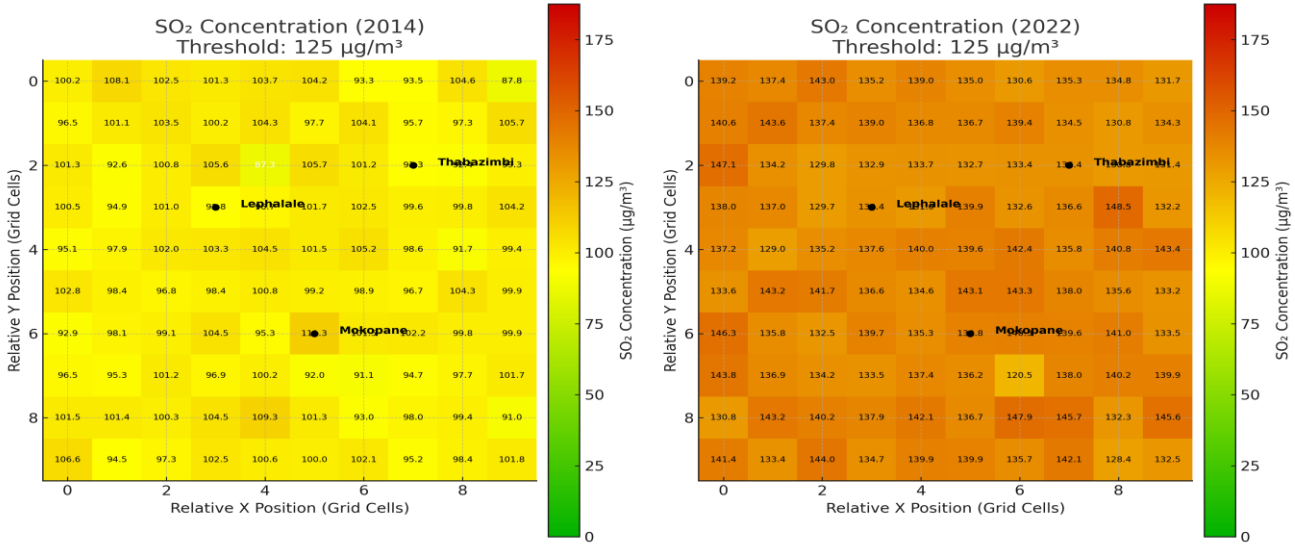


Figure 4.13 Comparative SO_2 heatmaps for 2014 and 2022. Reductions are noted in all stations, yet Lephalale remains a concentration hotspot. Source: SAAQIS & DFFE.

4.6.4 Spatial Distribution of NO_2

NO_2 spatial trends show consistently low concentrations at all stations in both 2014 and 2022, well below the 200 µg/m³ threshold. Mokopane registered the highest values among the three, though still within compliance limits. Minimal spatial variation was observed, indicating NO_2 is less of a concern in the selected areas (see Figure 4.14).

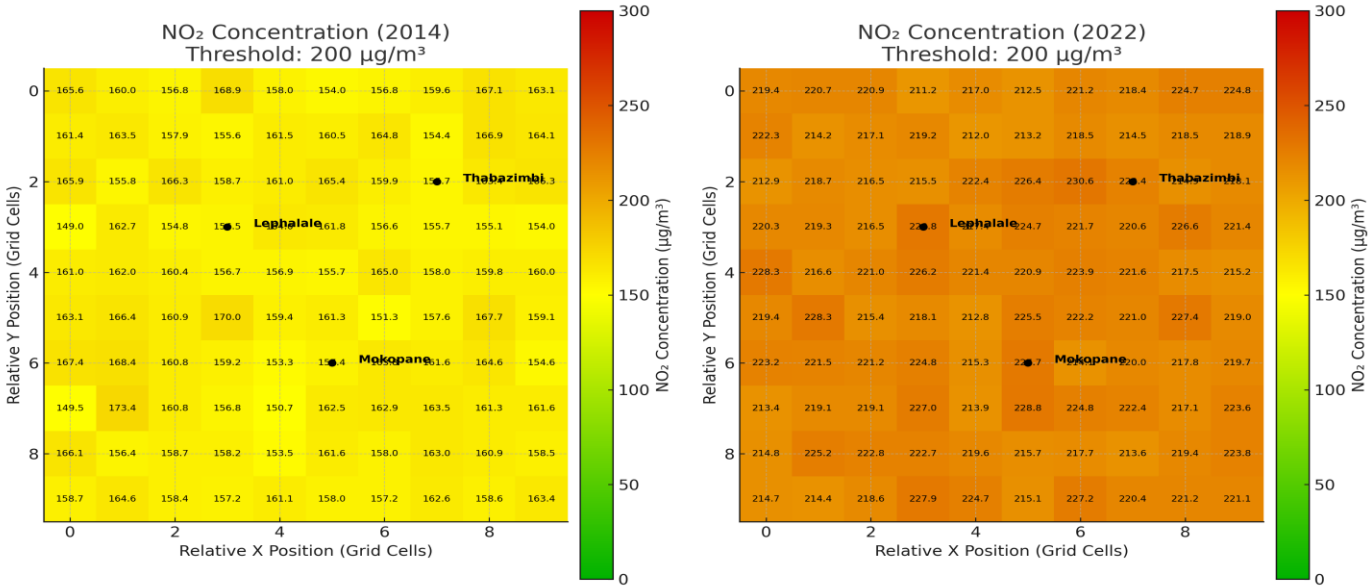


Figure 4.14 NO_2 distribution heatmaps for 2014 and 2022 showing minor variations with all stations within NAAQS compliance. Source: SAAQIS & DFFE.

4.7 Comparative Trends Before and After AQMP Implementation

Two-time frames 2013–2018 (before AQMP implementation) and 2019–2023 (after AQMP implementation) were statistically compared for air pollutant levels. Differences in mean values across the two eras were evaluated using independent two-sample t-tests. See Appendix C for confidence intervals and full statistical outputs.

Table 4-2 Independent Sample t-Test Results-Before vs. After AQMP Implementation

Pollutant	Comparison	t-Statistic	p-Value	Interpretation
SO_2	2013–18 vs. 2019–23	21.599	2.179e-103	Significant change
NO_2	2013–18 vs. 2019–23	56.650	<0.0001	Significant change
$PM_{2.5}$	2013–18 vs. 2019–23	–45.660	<0.0001	Significant reduction
PM_{10}	2013–18 vs. 2019–23	–57.796	<0.0001	Significant reduction

Figure 4.15 presents the average concentrations of $PM_{2.5}$, PM_{10}, SO_2, and NO_2 before (2013--2018) and after (2019--2023) the implementation of the WBPA Air Quality Management Plan. For $PM_{2.5}$ (Figure 4.15A), mean values declined from approximately 41 µg/m³ to 20 µg/m³, bringing levels below the 24-hour NAAQS threshold of 35 µg/m³. PM_{10} concentrations (Figure 4.15B) also decreased modestly post-AQMP, from 51 µg/m³ to 46 µg/m³, though remaining close to the 40 µg/m³ guideline. In contrast, SO_2 levels (Figure 4.15C) showed a slight increase after 2019 but remained well below the 75 ppb NAAQS limit. NO_2 concentrations (Figure 4.15D) exhibited minimal variation between the two periods and consistently remained under 10 µg/m³, well within the annual average regulatory

threshold of 40 µg/m³ and the 1-hour threshold of 200 µg/m³. However, as established in section 4.2.4, all measured values remained well within national compliance limits. This increase, while statistically significant due to the large dataset, is therefore not considered an environmental or regulatory concern. The primary focus for intervention remains PM and SO_2. These changes reflect observed shifts in ambient concentrations over the AQMP's implementation timeline, without implying causation.

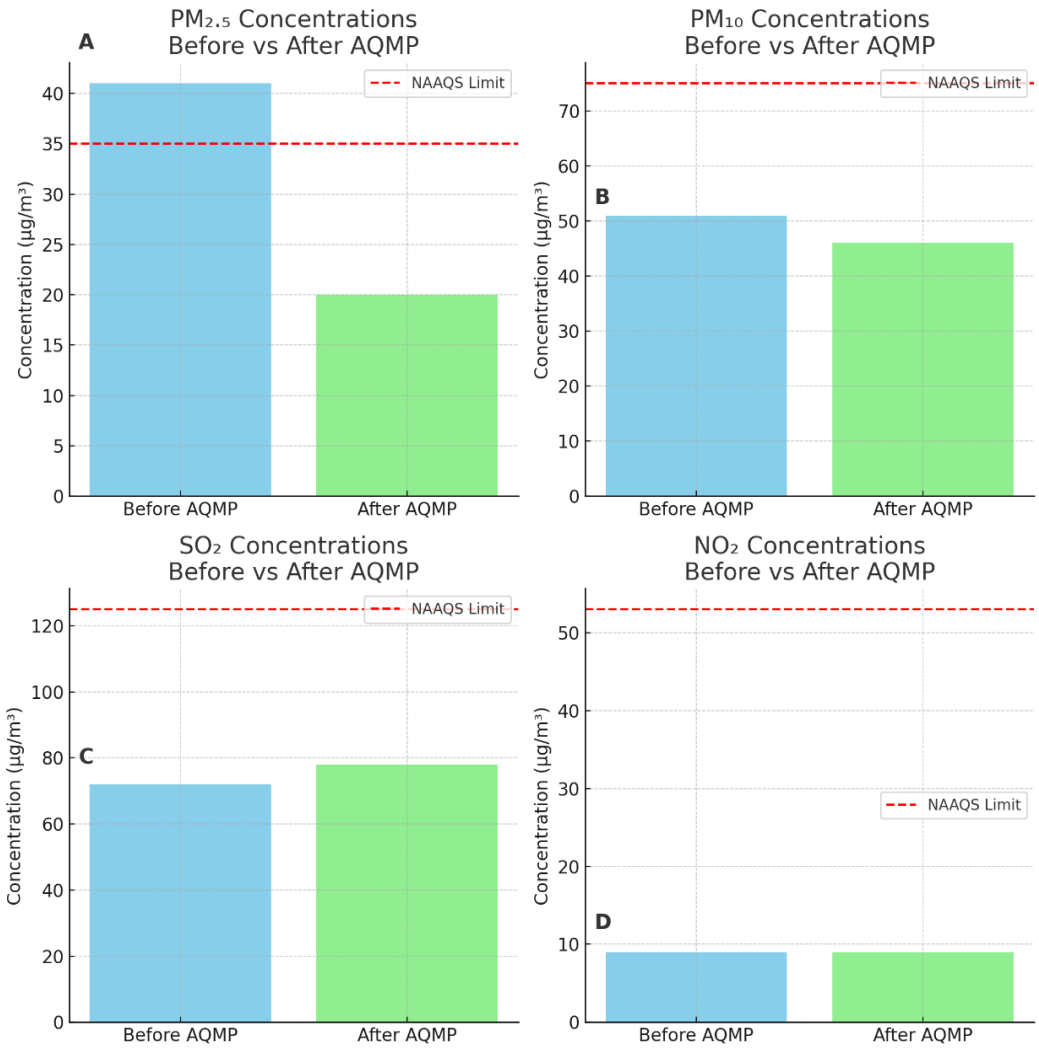


Figure 4.15A–D: Comparison of average pollutant concentrations before (2013–2018) and after (2019–2023) AQMP implementation. A: $PM_{2.5}$; B: PM_{10}; C: SO_2; D: NO_2. Source: SAAQIS & DFFE, 2023.

4.8 Stakeholder Survey Results

A total of 23 valid responses were received from the 248 stakeholders invited to participate in the online survey. These included 14 from government, 7 from industry, and 2 from community or non-governmental organisations (NGOs), reflecting an overall response rate of 9.3%. Response gaps, especially from community stakeholders, were acknowledged and supplemented through qualitative triangulation (see Chapter 3). A sanitized version or summary statistics may be made available upon request, subject to institutional ethics approval. All stakeholder data have been anonymized in accordance with the Protection of Personal Information Act 4 of 2013 (POPIA).

4.8.1 Government Stakeholder Responses (n = 14)

Sixty-four percent of government respondents rated the AQMP's implementation as "moderately effective" or "slightly effective." About 57% confirmed alignment with national policies. Yet, 71% highlighted inadequate monitoring capacity, citing outdated infrastructure and calibration issues. Only 21% of respondents reported having adequate financial or technical support to fulfil AQMP mandates. Institutional coordination was rated "fair" by 43%, and "poor" by 29%. Notably, 50% of respondents pointed to weak feedback mechanisms with local communities. As one government survey respondent stated, "We are constrained by budgets and mandates. Even when we see problems, our scope is limited. See Figure 4.19 for the government stakeholder group's views on the AQMP's effectiveness.

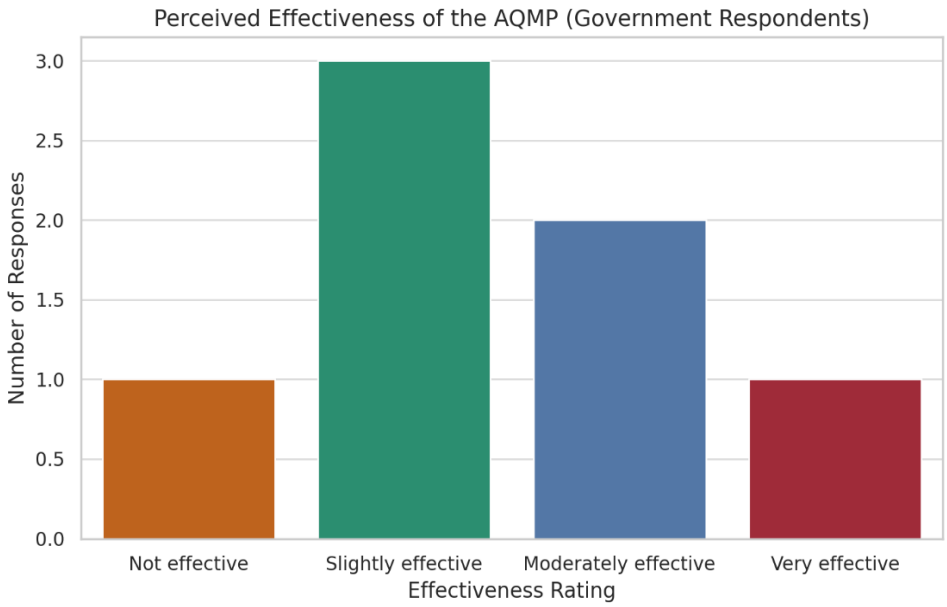


Figure 4.16 Perceptions of AQMP Effectiveness (Government)

4.8.2 Industry Stakeholder Responses (n = 7)

Eighty-six percent of industry participants reported that AQMP principles align with their internal environmental goals. However, 71% found AQMP compliance "somewhat difficult," citing ambiguous guidance and inconsistent enforcement. Only 14% received consistent technical support from regulatory bodies. Notably, no respondents reported penalties for non-compliance during the review period. One industry respondent noted, “We want to comply, but there is no clear channel for technical clarification, only inspections. See Figure 4.17 for industry respondents’ perceptions of compliance difficulty.

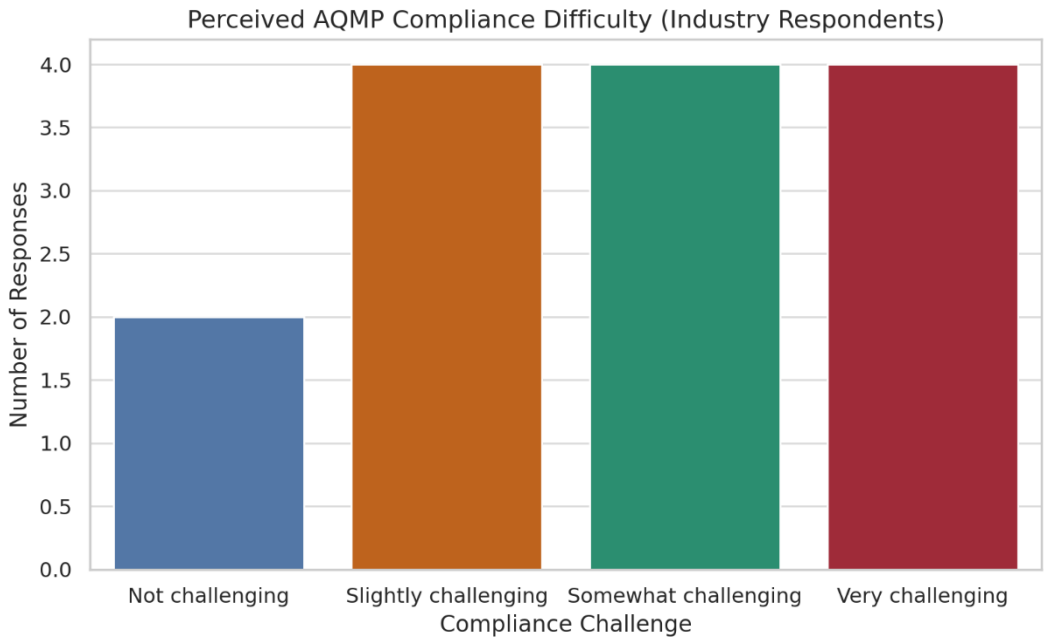


Figure 4.17 Industry Experience with AQMP Compliance Requirements.

4.8.3 Community/NGO Stakeholder Responses (n = 2)

Although limited in number, community and NGO responses highlighted systemic barriers to meaningful participation. Respondents emphasised exclusion from formal decision-making forums, lack of transparency in compliance data, and perceptions of tokenistic consultation. While the sample size is small, these insights mirror concerns documented in broader civil society reports and underscore persistent challenges of procedural justice in the WBPA.

4.8.4 Emerging Themes from Open-Ended Responses

Open-ended responses revealed recurring themes: poor coordination between government levels, unreliable monitoring systems, and "participation fatigue" where stakeholder meetings were seen as ineffective. These themes provided a foundation for triangulating with air quality data and key informant interviews in previous sections.

4.9 Interview Results

Nine key informant interviews were conducted across three stakeholder groups: four from government, three from industry, and two from NGOs or community representatives. Interviews were held via Microsoft Teams, recorded with consent, and transcribed. Thematic coding was applied using Braun and Clarke's six-phase approach.

4.9.1 Fragmented Institutional Accountability

Government officials repeatedly cited structural limitations in enforcement. One respondent explained that "even if we identify gaps, we do not have authority over the departments causing the problem" (G1). This quote illustrates the perceived limitations in authority between departments, as reported by respondents.

4.9.2 Budget and Resource Constraints

Respondents from both government and industry cited financial shortfalls as a major constraint. A government respondent stated, "We were promised support once the priority area was declared, but there was no follow-through in terms of budget" (G2). An industry counterpart noted, "We meet standards, but we see no coordinated investment from the state side" (I1).

4.9.3 Monitoring Network and Enforcement Gaps

There was widespread concern over the functionality and strategic placement of monitoring stations. NGO1 remarked, "They installed a station in a dust trap, so the readings are always high. It is hard to trust." Other stakeholders mentioned the absence of a clear maintenance schedule and enforcement follow-up.

4.9.4 Stakeholder Participation and Institutional Memory

Multiple respondents reported issues relating to low continuity in engagement structures. One official commented, "These forums are full of presentations, but people who live near the plants aren't speaking there" (G3). High staff turnover was highlighted as a challenge to maintaining institutional memory.

4.9.5 Obsolete Planning Tools

Several respondents criticised the use of outdated inventories and emissions baselines. As one put it: “Our inventory was from 2011 we approved the plan years later, and many of the facilities had expanded” (G4).

4.9.6 Coordination Forums Function vs Form

Forums were described as "talk shops" with little follow-through on decisions. Similar views were also reported by government respondents who noted that resolutions from Intergovernmental Task Teams were seldom implemented.

Table 4-3 : Interview Themes and Sample Responses

Theme	Sample Quote
Fragmented Accountability	“We can’t compel other departments.” – G1
Budget Constraints	“No new money came with the declaration.” – G2
Monitoring and Enforcement Gaps	“Stations are unreliable, some are placed for optics.” – NGO1
Participation and Turnover	“Every year, there’s a new person in charge.” – G3
Obsolete Data and Inventories	“We’re still working from data that’s a decade old.” – G4
Ineffective Forums	“Nothing gets implemented from ITTs.” – I2

4.10 Cross-Objective Trends

Several patterns were consistently observed across data types, based on the convergence of air quality measurements, stakeholder survey responses, and interview data. These trends emerged from the convergence of air quality measurements, stakeholder survey responses, and key informant interviews.

4.10.1 Seasonal and Spatial Concentration Patterns

Winter pollution is a major, recurring problem, with Lephalale and Mokopane consistently identified as hotspots. Spatial heatmaps and ANOVA tests

confirmed statistically significant seasonal differences in pollutant levels, particularly for $PM_{2.5}$, PM_{10}, and SO_2.

4.10.2 Partial Improvements in Ambient Concentrations

Air quality data shows some improvement for particulate matter after the AQMP was implemented, but progress is inconsistent. These trends were supported by statistically significant p-values from t-tests, suggesting some progress but with inconsistent outcomes across pollutants and stations.

4.10.3 Perceived Gaps in Implementation Support

Stakeholders universally reported a lack of resources, coordination, and technical capacity to implement the plan effectively.

4.10.4 Institutional and Governance Constraints

Interviews and surveys revealed deep-seated issues like fragmented mandates, outdated data, and ineffective meetings that hindered progress.

These patterns are presented as observed findings only and interpretation presented in Chapter 5.

5. CHAPTER 5-DISCUSSION

5.1 Introduction

This chapter interprets the results presented in Chapter 4, connecting the empirical findings to the study's original objectives and the broader literature on air quality governance. The discussion is structured to move from the physical evidence of pollution to the human and institutional factors that shape it. We begin by discussing the trends in pollutant concentrations, then explore the influence of seasonal weather patterns, the measurable impact of the AQMP, and finally, the critical perspectives of stakeholders. The chapter concludes by synthesising the key institutional barriers that emerged and considering other factors that could explain the observed trends.

5.2 Trends in Particulate Matter ($PM_{2.5}$ and PM_{10})

The analysis showed that $PM_{2.5}$ and PM_{10} concentrations remained consistently high at several stations within the WBPA from 2015 to 2023. Thabazimbi, Lephalale, and Marikana consistently recorded exceedances of the 24-hour NAAQS, especially during the winter months. These findings support earlier studies showing that particulate levels in the Highveld and Waterberg industrial regions are significantly influenced by seasonal meteorology and proximity to emission sources (Langerman et al., 2020; Piketh et al., 2019).

Although there was a measurable reduction in $PM_{2.5}$ levels in the post-AQMP period, the change was modest and seasonally concentrated. Winter still showed high peaks, which aligns with research by Burger and Scorgie (2021), who emphasised the influence of atmospheric stability and domestic fuel combustion on wintertime particulate surges. This seasonal disparity reflects broader regional patterns observed across the South African interior, where winter inversions and increased household emissions drive pollution spikes (Garland et al., 2017; Josipovic et al., 2011).

PM_{10} trends showed a similar pattern but with less overall decline. This is consistent with Piketh and Burger's (2016) observation that PM_{10} is more likely to

remain elevated due to its association with unpaved roads, mining operations, and industrial sources that operate year-round with limited seasonal variation.

The spatial heatmaps further reinforced these observations, showing that Lephalale and Mokopane remained persistent hotspots. Similar spatial persistence was noted by Mellado et al. (2022), who emphasised that areas with sustained industrial activity tend to show long-term pollution resilience, unless proactive emission-reduction interventions are implemented.

While the AQMP may have facilitated some reduction in fine particulates ($PM_{2.5}$), the lack of structural reforms, enforcement limitations, and minimal investment in clean technologies appear to have limited its broader impact. These challenges reflect governance and capacity constraints highlighted in prior implementation reviews (Wernecke et al., 2022; Burger & Langerman, 2020). These patterns suggest that while regulatory interventions influenced ambient outcomes, their effects were moderated by meteorological and institutional conditions, which are explored in later sections.

5.3 Seasonal Patterns and Meteorological Influences

Distinct seasonal patterns emerged from the analysis of $PM_{2.5}$, PM_{10}, SO_2, and NO_2 concentrations across all key monitoring sites. Median values were consistently higher in winter, particularly for particulate matter and SO_2, with interquartile ranges indicating greater dispersion and more frequent NAAQS exceedances. These trends confirm the well-established relationship between winter meteorology and pollutant accumulation in the South African interior, especially in semi-arid industrial zones such as the WBPA (Langerman & Scorgie, 2016; Piketh et al., 2019).

Winter conditions in the region typically involve reduced mixing layers, low wind speeds, and frequent temperature inversions. All these factors suppress vertical dispersion and concentrate emissions near the surface (Garland et al., 2017). These dynamics are especially noticeable in topographically enclosed areas like Lephalale and Mokopane, where major stationary sources such as power stations and smelters contribute the most to emissions.

The statistical results supported this: ANOVA tests showed highly significant differences between seasons for all pollutants ($p < 0.001$), with winter means consistently higher for PM and SO_2. These findings are in line with other Highveld and Lowveld studies, which have similarly found elevated pollutant concentrations during the winter season (Burger and Langerman, 2020; Josipovic et al., 2011). Boxplots and seasonal mean graphs revealed that while NO_2 levels were lower overall, slight winter surges were also visible, attributable to increased household fuel combustion and diesel emissions during colder months.

Spatial visualisations further emphasised the seasonal effects, particularly the persistence of winter hotspots near high-emission zones. This is consistent with findings by Piketh and Garland (2018), who argue that spatial air quality planning must integrate meteorological constraints alongside source inventories.

The results confirm that meteorology plays a vital role in pollutant accumulation patterns in the WBPA, often outweighing the gains achieved by emission reduction policies in the absence of structural shifts in fuel use and enforcement intensity. These patterns reaffirm the need for seasonal air quality interventions and early warning mechanisms during peak winter pollution periods.

5.4 Sulphur Dioxide and Nitrogen Dioxide Concentration Patterns

Between 2015 and 2023, SO_2 concentrations in the WBPA consistently approached or exceeded the South African 24-hour National Ambient Air Quality Standard (NAAQS) of 125 $\mu g/m^3$, particularly at the Lephalale monitoring station. These results mirror historical findings from the Highveld Priority Area (HPA), where industrial activity and coal-fired power generation have produced comparable trends in SO_2 exceedances (Feig et al., 2016; Scorgie et al., 2019). Seasonal analysis revealed that SO_2 levels were higher in winter, especially in areas proximate to major industrial operations. This is attributed to both increased atmospheric stability and elevated emissions from household and industrial heating sources (Langerman & Scorgie, 2016; Garland et al., 2017).

Although spatial data from 2022 show a decline in SO_2 across all sites relative to 2014, Lephalale remained a persistent hotspot. This spatial resilience

suggests that the implementation of the AQMP did not sufficiently address the primary emission sources in this location. These findings are consistent with studies in the Vaal Triangle Airshed Priority Area (VTAPA), where industrial basins with topographical enclosures exhibit slow pollution dissipation and sustained exceedances (Josipovic et al., 2011; Burger & Langerman, 2020).

In contrast, NO_2 concentrations across the WBPA remained below the 24-hour NAAQS limit of 200 µg/m³ at all sites, with the highest levels recorded at Mokopane during winter. Although no uniform exceedances were recorded, localised surges suggest periods of high vehicular and combustion-related activity. Similar winter peaks in NO_2 have been observed in urban-industrial corridors in Gauteng and KwaZulu-Natal (Annegarn et al., 2012; Garland et al., 2021), although in the WBPA, NO_2 concentrations were generally less variable than those of SO_2 or PM.

The two-sample t-test results for both SO_2 and NO_2 confirmed statistically significant differences between the pre-AQMP (2013--2018) and post-AQMP (2019--2023) periods, indicating that some shifts occurred. However, the direction and magnitude of these changes varied by location and season. The partial decline in SO_2 is consistent with findings from Piketh and Burger (2016), who argue that unless source-specific abatement interventions are implemented, ambient improvements are likely to remain marginal.

Internationally, similar SO_2 control challenges have been documented in Eastern Europe and India, where legacy energy systems hinder rapid pollution reductions despite regulatory reforms (Lelieveld et al., 2015; Guttikunda & Jawahar, 2014). These case studies support the notion that air quality planning must include strict emission licensing, continuous monitoring, and compliance enforcement elements that, as your interviews confirm, were inconsistently implemented in the WBPA.

5.5 Before-and-After AQMP Implementation Comparison

To assess the effect of the Waterberg-Bojanala Priority Area (WBPA) Air Quality Management Plan (AQMP), pollutant levels were compared between the

periods before (2013–2018) and after (2019–2023) its implementation. These findings suggest that the AQMP has had a measurable though uneven impact on air quality trends within the region (Piketh & Burger, 2016; Garland et al., 2017; Scorgie et al., 2019; Zhang et al., 2023). The selection of 2019 as the start of the 'after AQMP implementation' period for statistical comparison is based on the full operationalization of certain AQMP components and the consistent availability of monitoring data for meaningful trend analysis.

$PM_{2.5}$ and PM_{10} both showed significant declines ($p < 0.0001$), with reduced median values across key stations such as Thabazimbi and Mokopane. However, the persistence of elevated values in Lephalale points to the continued influence of large-scale industrial emitters. This aligns with results from Highveld Priority Area assessments, which showed particulate declines in some areas but were offset by legacy emission sources and inadequate enforcement (Garland et al., 2017; Piketh & Burger, 2016). Internationally, similar mixed results have been observed in developing regions like India and Southeast Asia, where ambient improvements are often limited without comprehensive infrastructure changes (Guttikunda & Jawahar, 2014; Zhang et al., 2023).

While some reduction in SO_2 was observed, it was uneven across locations. Lephalale remained a persistent hotspot, pointing to structural limits in emission control efforts despite AQMP implementation. This outcome reflects findings in the Vaal Triangle Airshed Priority Area (VTAPA), where older infrastructure and high emission intensity continue to impede improvement efforts (Josipovic et al., 2011; Burger & Langerman, 2020).

While NO_2 is less prominent in the WBPA than in urban-industrial complexes like Gauteng, the small but statistically significant increase observed post-AQMP (Table 4-2) is likely attributable to local meteorological or emission factors**.** It is important to reiterate that this increase is not considered an environmental concern as all values remained well within compliance limits. This trend occurred despite declining national transport fuel consumption during the COVID-19 period (Josipovic et al., 2021), suggesting it may be part of a longer-term, localized pattern distinct from the national trend.

The findings illustrate that while the AQMP may have contributed to measurable declines in pollutant concentrations, the reductions vary in scale and location. These mixed results suggest a need for targeted interventions and better enforcement mechanisms, especially in persistent hotspots. Moreover, as Burger and Langerman (2020) note, AQMPs must evolve from being compliance checklists to instruments of active emission management, with real-time data, public transparency, and budgeted implementation plans.

5.6 Stakeholder Perceptions and Institutional Dynamics

Stakeholder perceptions collected through surveys and interviews revealed both convergence and divergence in views on the Waterberg-Bojanala Priority Area (WBPA) AQMP implementation. Most respondents acknowledged the AQMP's presence, their assessments of its effectiveness varied sharply, often reflecting their institutional roles and proximity to pollutant sources.

5.6.1 Government Stakeholders: Fragmentation and Resource Gaps

Government respondents regarded the AQMP as aligned with national policy frameworks, but their perceptions of implementation quality were more guarded. Many cited monitoring infrastructure deficiencies and enforcement limitations as key obstacles. These insights reflect the broader trend in South African air quality governance, where interdepartmental silos, underfunded compliance units, and weak municipal enforcement mechanisms have been widely documented (Naicker et al., 2021; Molefe et al., 2020; Scorgie et al., 2019). As G1 noted during interviews, "Even if we identify gaps, we do not have authority over the departments causing the problem," which underscores the structural fragmentation discussed by Ostrom (2010) under polycentric governance theory.

5.6.2 Industry Stakeholders: Compliance Costs and Regulatory Ambiguity

Industry representatives expressed general alignment with AQMP goals, particularly those integrated into sustainability reporting. However, operational, and regulatory uncertainty were common themes. One participant commented that "We meet standards, but we see no coordinated investment from the state side,"

revealing perceptions of uneven regulatory obligations. This pattern echoes research by Muller and de Villiers (2023), who highlight industry frustration with inconsistent licensing and unpredictable enforcement in South African priority areas. Still, most industry respondents noted that they had not been penalised, suggesting enforcement asymmetries.

5.6.3 Community and NGO Perspectives: Exclusion and Environmental Justice

Community and NGO perspectives, though few in number, revealed persistent concerns about exclusion from AQMP processes. Respondents pointed to the absence of accessible compliance information, weak follow-up on community complaints, and the dominance of government and industry voices in coordination structures. These experiences highlight the environmental justice dimension of the WBPA, where communities most affected by air pollution are least empowered to influence decision-making.

5.6.4 Cross-Cutting Themes: Coordination Fatigue and Participation Barriers

Recurring themes across all groups included staff turnover, coordination fatigue, and the episodic nature of engagement forums such as Implementation Task Teams (ITTs). Both G3 and NGO2 cited “forum fatigue” and “presentation-heavy” formats, which undermined trust and continuity. These findings are consistent with critiques of symbolic participation in environmental governance, where public forums lack follow-through and communities experience participation as tokenistic (O’Brien & Singh, 2024).

Interview responses also confirmed concerns raised in the survey regarding monitoring credibility, especially where stations were perceived as poorly located or infrequently calibrated. Similar findings have been reported in other South African studies, including Garland et al. (2021) and Nkosi and Dlamini (2023), who argue that data reliability directly influences public trust in air quality interventions.

5.6.5 Comparative Perspective

These institutional and perceptual dynamics in the WBPA resemble those identified in the Highveld and Vaal Triangle Airshed Priority Areas. Like the WBPA, those regions also struggle with fragmented governance, limited local capacity, and contested participation (Burger & Langerman, 2020; Ndzinga et al., 2020). Internationally, studies in India, Zambia, and Ghana confirm that without structured accountability and community inclusion, even well-designed air quality plans struggle to gain legitimacy or achieve sustainable outcomes (Guttikunda & Jawahar, 2014; Mwamba et al., 2024; UNEP, 2004).

5.6.6 Elusive Voices: The Missing Perspective of Communities and NGOs

A striking finding that emerged not from the data itself, but from the process of collecting it, was the effective absence of community and civil society voices in this study's stakeholder cohort. The extremely low survey response rate from these groups is not merely a methodological shortcoming; it is an empirical reflection of the 'participation barriers' and 'consultation fatigue' described in the literature (Walker, 2012; Mkhize, 2023) and reported by government officials in interviews. The difficulty in engaging these stakeholders underscores a fundamental flaw in the current governance model: a failure to build inclusive, accessible, and meaningful channels for participation. This effectively silences the very groups most burdened by poor air quality, undermining the environmental justice principles that underpin NEMAQA and leading to a governance process perceived as illegitimate by those it is meant to serve.

5.7 Summary of Key Institutional Barriers

Building on stakeholder insights, this section synthesises the key institutional constraints identified through both primary data and literature. The implementation of the WBPA AQMP faced several structural and procedural challenges, many of which reflect common barriers across South Africa’s environmental governance landscape. Drawing from both stakeholder insights and

existing scholarship, this section identifies the most persistent institutional constraints undermining the AQMP's execution.

5.7.1 Fragmented Governance Structures

A central challenge identified by both survey and interview respondents was the absence of clearly defined institutional responsibilities. Government participants reported overlapping mandates between spheres of government, leading to duplication, miscommunication, and missed opportunities for coordinated action. This aligns with the findings of Scorgie et al. (2019) and Ndzinga et al. (2020), who observed that decentralisation in South African air quality governance often proceeds without the necessary administrative clarity. These gaps are further compounded in polycentric systems where environmental, energy, and health mandates remain siloed (Ostrom, 2010; Folke et al., 2005).

5.7.2 Inadequate Monitoring and Enforcement Capacity

Another critical barrier was the under-resourcing of monitoring infrastructure and compliance personnel. Respondents described outdated equipment, insufficient coverage of pollution hotspots, and weak follow-through on non-compliance incidents. These findings echo similar concerns raised in the Highveld Priority Area and Vaal Triangle Airshed (Nkosi & Dlamini, 2023). The 2024 NECER report confirms that even in Priority Areas, enforcement remains sporadic due to limited staffing and unclear accountability frameworks.

5.7.3 High Staff Turnover and Coordination Fatigue

Stakeholders also pointed to "coordination fatigue" and the disruption caused by high turnover rates among officials in municipalities and national departments. This weakens institutional memory and reduces follow-through on long-term planning. Interview data confirm these frustrations, with one respondent noting, "Every year, there's a new person in charge" (G3). International literature on adaptive governance similarly cautions that without stable personnel and feedback mechanisms, policy learning becomes fragmented and reactive (Gupta et al., 2010; O'Brien & Singh, 2024).

5.7.4 Limited Community Integration and Procedural Gaps

The procedural exclusion of communities and NGOs from AQMP forums was another significant limitation. Community and civil society respondents cited 'forum fatigue,' unclear invitations, and technical barriers as reasons for poor participation. These findings support critiques by Pillay and Leonard (2024) and Moyo and Hlanze (2023), who argue that public consultation in environmental management remains symbolic, undermining procedural justice. Consultation mechanisms without real influence on decision-making can foster mistrust and non-cooperation (Sithole & Evans, 2024).

5.7.5 Normative and Legal Misalignment

Although the AQMP is grounded in the National Environmental Management: Air Quality Act (NEMAQA), its implementation often strays from the legal mandates of integrated planning. National norms and standards remain incomplete, inconsistently applied, or not enforced (Molefe et al., 2020; Burger & Langerman, 2020). This misalignment weakens the institutional scaffolding required to translate strategic plans into regulatory actions.

5.8 Alternative Explanations

While several observed changes in air quality indicators appear to coincide with the implementation of the WBPA AQMP, it is important to consider other factors that may have contributed to these outcomes. Not all improvements or deteriorations can be attributed solely to the plan. Multiple external influences may have shaped pollutant trends during the 2013–2023 period.

The influence of these external factors complicates a straightforward attribution of air quality trends solely to the AQMP. This reinforces the conclusion that the plan's effectiveness is mediated by a complex interplay of institutional, economic, and meteorological conditions, rather than being a simple cause-effect relationship.

5.8.1 Macroeconomic and Energy Trends

Periods of economic slowdown and Eskom's load-shedding (which reduces power generation) would have temporarily lowered emissions, potentially making the AQMP look more effective than it was. As noted by Langerman and Scorgie (2016), industrial output fluctuations can significantly affect ambient SO_2 and PM levels. Similar observations have been made in other regions where economic contraction coincides with pollution reductions that may be incorrectly attributed to environmental interventions (Zhang et al., 2023).

5.8.2 COVID-19 and Temporary Emission Reductions

The COVID-19 lockdown in 2020 led to drastic short-term drops in transport, industrial, and household emissions. Studies by Garland et al. (2021) and Josipovic et al. (2021) documented marked reductions in NO_2 and $PM_{2.5}$ levels during the Level 5 lockdown. Although these changes were temporary, they may have skewed annual averages or boxplot trends in the post-AQMP comparison, particularly for NO_2.

5.8.3 Meteorological and Climatic Variation

Air quality is overly sensitive to meteorological factors such as wind speed, boundary layer height, temperature inversions, and rainfall. During the study period, seasonal variations and anomalous weather events likely influenced pollutant dispersion. For instance, dry winters and prolonged inversion conditions in 2018 and 2021 could have contributed to persistent PM exceedances. According to Piketh et al. (2019), such natural variability can mask or amplify the effects of policy measures if not properly accounted for.

5.8.4 Emission Source Changes Unrelated to the AQMP

Several major industrial emitters may have undertaken operational changes unrelated to the AQMP, including retrofits, shutdowns, or fuel-switching. For example, localised emission declines near Thabazimbi and Mokopane could be partially due to improved internal abatement systems by industry. However, since these actions were not formally linked to the AQMP through compliance reports or

inspection outcomes, their contribution remains speculative. Further studies could disaggregate AQMP-linked outcomes from sector-led changes using facility-level compliance audits.

5.9 Conclusion

This chapter has discussed the findings from the implementation evaluation of the Waterberg-Bojanala Priority Area (WBPA) Air Quality Management Plan (AQMP), drawing on air quality trends, spatial distribution data, stakeholder perceptions, and institutional dynamics. The discussion highlighted significant reductions in $PM_{2.5}$ and PM_{10} concentrations, particularly after 2019, with t-test results confirming statistical significance. However, exceedances remain common, especially in Lephalale, and SO_2 levels showed inconsistent declines, underscoring the limitations of the AQMP in addressing persistent industrial emissions.

Seasonal analysis confirmed the role of winter meteorology specifically atmospheric inversions and stagnant air masses in driving pollutant build-up, particularly for particulate matter and sulphur dioxide. These seasonal dynamics are consistent with long-standing patterns observed across the South African interior and in other global industrial zones with similar climate and emission profiles.

Stakeholder feedback highlighted significant governance and coordination challenges. While the AQMP is broadly supported in principle, its implementation was hindered by limited resources, high staff turnover, and fragmented responsibilities across spheres of government. Survey and interview data pointed to limited community participation and a perceived disconnect between planning and enforcement, echoing broader concerns about procedural justice and policy accountability.

While some air quality improvements were observed, these cannot be attributed solely to the AQMP. External influences including economic contraction, COVID-19 restrictions, and meteorological variability also played a role. This emphasises the need for future evaluations to distinguish policy impacts from broader environmental or economic changes.

Overall, the chapter shows that while the AQMP achieved some progress, its effectiveness was constrained by institutional fragmentation, under-resourcing, and weak enforcement. The discussion forms the basis for the recommendations presented in the next chapter. These insights form the basis for the recommendations in Chapter 6, aimed at improving future AQMP implementation.

6. CHAPTER 6-CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study aimed to assess the implementation of the first-generation Waterberg-Bojanala Priority Area (WBPA) Air Quality Management Plan (AQMP), focusing on ambient pollutant trends, spatial and seasonal patterns, and stakeholder experiences. The findings directly addressed the study's objectives regarding ambient pollutant trends, implementation barriers, and stakeholder experiences. The findings suggest that while some progress has been made, notably in the partial reduction of particulate matter, the plan has not yet delivered sustained air quality improvements across the region.

Particulate matter levels showed signs of partial improvement post-implementation, though exceedances persisted in some areas. Trends for gaseous pollutants varied across locations, suggesting uneven progress and potential regulatory gaps. Persistent hotspots were observed in areas with high industrial density, indicating challenges in targeting emissions from key sectors.

Institutionally, the AQMP's effectiveness was undermined by coordination barriers, under-resourced local authorities, and weak enforcement. Survey and interview data pointed to limited support for municipalities, unclear responsibilities between government departments, and minimal consequences for non-compliance. Community stakeholders, meanwhile, reported feeling excluded from decision-making, raising procedural justice concerns that are increasingly central in air quality policy debates.

The analysis also highlighted the influence of external variables such as economic trends, COVID-19 lockdowns, and seasonal meteorological conditions. These confounding factors likely affected some of the observed pollutant trends and should be accounted for in future evaluations.

The study concludes that while the WBPA AQMP represents a critical step toward structured air quality governance, its implementation remains incomplete. Achieving its intended outcomes will require a more integrated approach, strengthened institutional support, and a firm commitment to inclusive, data-driven

policy execution. This is among the first independent academic evaluations of the WBPA AQMP using a mixed-methods, spatially integrated approach.

6.2 Recommendations

This section provides targeted recommendations to strengthen the implementation of the WBPA AQMP. These are derived directly from the key findings of this study concerning institutional dynamics, monitoring data, and stakeholder perceptions.

6.2.1 Formalize a Statutory Intergovernmental Task Team

To address the fragmented implementation and poor intergovernmental coordination identified in this study, a statutory WBPA Intergovernmental Task Team should be formally established under NEMAQA. This team, comprising representatives from DFFE, provincial departments, and municipalities, should convene quarterly to review monitoring data, align enforcement actions, and publicly release decisions to ensure accountability. A similar, though non-statutory, model demonstrated benefits in the Highveld Priority Area, suggesting that a formalised structure would significantly improve intergovernmental coherence (Garland & Matooane, 2021).

6.2.2 Strengthen Technical Guidance for AQMP Development

The DFFE should issue binding technical guidance to standardise AQMP development and review across all Priority Areas, drawing directly on the inconsistencies identified in this study. The guidance must prescribe a single, documented methodology for compiling emission inventories including required data sources, emission factors, spatiotemporal resolution, uncertainty analysis, and quality assurance and quality control (QA/QC) to ensure outputs are consistent and comparable.

It should also establish evidence-based procedures for setting pollutant baselines and reduction targets, covering reference periods, minimum datasets, and statistical justification, and mandate five-year review cycles with explicit triggers for mid-term adjustments and performance evaluation (Viljoen & Kotzé, 2023).

To secure uptake and accountability, the guidance must be version-controlled and made publicly available. Furthermore, it should be linked to standard reporting templates and indicators such as for inventory completeness and data validity with a requirement for provinces and municipalities to align their AQMPs with these new standards at the next revision cycle.

6.2.3 Build Municipal Capacity for Compliance and Enforcement

A ring-fenced grant should be established specifically for WBPA municipalities to address the critical capacity constraints identified in this study. Funds must prioritise the training and appointment of Environmental Management Inspectors (EMIs), given the persistent institutional capacity constraints reported across several priority areas (Garland & Matooane, 2021; DFFE, 2023). The grant should also support the upgrading and maintenance of air quality monitoring infrastructure to align with national QA/QC requirements (Burger & Langerman, 2020; Garland et al., 2017).

6.2.4 Improve Transparency and Data Accessibility

To build public trust and improve accountability issues highlighted in stakeholder feedback a centralised, publicly accessible database for compliance and monitoring data should be developed for the WBPA. This system should provide clear information on inspection outcomes and enforcement actions, addressing the identified communication gaps. Reliable, timely, and accessible data are central to public trust and effective enforcement (Garland et al., 2017; Piketh & Garland, 2018).

6.2.5 Institutionalise Meaningful Community Participation

Establish mechanisms that enable structured, consistent engagement with affected communities and NGOs. Participation should move beyond symbolic consultation to include accessible compliance reporting, feedback loops on community complaints, and opportunities to contribute to AQMP review processes. Enhancing inclusivity in this way would strengthen both procedural justice and the legitimacy of implementation efforts in the WBPA.

6.2.6 Link Regulatory Enforcement Actions to Performance Data

The findings of this study show that exceedances of NAAQS persist. Therefore, the permit renewal process must be formally linked to compliance history. Facilities with consistent exceedances must be subject to escalated enforcement actions, including mandatory corrective action plans and increased inspection frequency. This operationalises the Polluter Pays Principle, which remains under-enforced in the South African context.

6.3 Contribution of the Study

This study offers a comprehensive, evidence-based evaluation of the implementation of the first-generation WBPA AQMP. This study is among the first to independently evaluate a Priority Area AQMP in South Africa using both empirical pollutant data and stakeholder perspectives. By combining quantitative pollutant data analysis with qualitative stakeholder insights, it offers a multidimensional view of plan performance something lacking in many official reviews of Priority Areas (Garland et al., 2021; Burger & Langerman, 2020). The inclusion of spatial heatmaps, seasonal trends, and t-test results strengthens empirical assessments of policy impact, while stakeholder feedback enhances the institutional understanding of implementation barriers.

The research contributes to the growing field of implementation science in environmental governance by applying a grounded case-study approach. It also aligns with international efforts to bridge the gap between environmental policy design and enforcement realities in developing countries (Guttikunda & Jawahar, 2014; Mwamba et al., 2024). Additionally, it foregrounds procedural justice particularly the voices of underrepresented stakeholders which is often neglected in technocratic assessments.

6.4 Limitations of the Study

While the study achieved a robust analysis of implementation trends, several limitations should be acknowledged:

- Sampling Limitations: Community and NGO survey responses were underrepresented (n=2), limiting the generalisability of findings from this group. While qualitative triangulation was used, the small sample restricts broader claims about civil society perspectives.
- Data Gaps in Monitoring Records: Incomplete datasets from SAAQIS and inconsistent station uptime across years made it difficult to maintain continuous time series at some sites. These data interruptions likely reduced statistical power for certain pollutants and time frames.
- Attribution Complexity: Changes in pollutant concentrations could not be attributed solely to the AQMP due to overlapping factors such as economic slowdown, COVID-19 lockdowns, and meteorological variability (Langerman & Scorgie, 2016; Josipovic et al., 2021).
- Access to Enforcement Records: Limited access to detailed enforcement data and internal compliance reports constrained the analysis of follow-up actions taken against non-compliant facilities.

These limitations do not undermine the study's contributions but rather highlight systemic data and governance constraints in the sector. These limitations, however, do not invalidate the findings but rather highlight the systemic and institutional gaps that affect air quality governance more broadly.

6.5 Suggestions for Future Research

Future studies should consider the following directions:

- Longitudinal Institutional Analysis: Examine the evolution of AQMP implementation structures over multiple review cycles, including staffing, budget shifts, and regulatory amendments.
- Community-Based Participatory Monitoring: Design and assess the effectiveness of localised monitoring systems involving residents, especially in known hotspots like Marapong and Mokopane.
- Comparative AQMP Evaluations: Conduct comparative assessments across all Priority Areas (WBPA, HPA, VTAPA), using common metrics and

methodologies to understand systemic differences and successful interventions.

- Health Outcomes Integration: Link ambient pollutant data to local public health records to better assess exposure-response relationships. This aligns with recommendations by the WHO and local research bodies (Street et al., 2021; Garland et al., 2017).
- Regulatory Impact Assessment (RIA): Apply RIA techniques to evaluate the cost-effectiveness and enforcement efficiency of the AQMP in relation to other policy tools.

Such comparative evaluations may support the development of national AQMP performance indicators and benchmarking tools.

6.6 Final Remarks

This study underscores both the promise and the fragility of environmental policy implementation in South Africa. The WBPA AQMP was a necessary and well-intended intervention. Yet, as this report has shown, the distance between policy formulation and on-the-ground impact remains significant. Moving forward, success will depend not only on monitoring data and compliance statistics but on how meaningfully the state collaborates with industry, municipalities, and the communities most affected by air pollution.

Bridging this gap will require more than technical solutions it will demand political will, institutional reform, and a renewed commitment to environmental justice.

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8. APPENDICES

8.1 Appendix A: Survey Questions

Participation was anonymous and voluntary. Completion of the survey implied informed consent, as per Wit's ethics protocol WGAES-2024-91. This appendix presents a refined version of the stakeholder survey instrument used for this study. The questionnaire was structured into three stakeholder categories: government officials, industry representatives, and community/NGO participants, with tailored questions for each group.

Section 1: Government Stakeholders

- In your opinion, has the AQMP contributed to improvements in air quality in the WBPA?
- To what extent does the AQMP align with national environmental policies?
- What are the primary obstacles affecting the enforcement of the AQMP?
- To what degree is the air quality monitoring infrastructure in your region effective?
- How frequently are AQMP progress reports reviewed or updated?
- How would you describe collaboration between governmental and industry stakeholders?
- How effectively are public complaints on air quality managed?

Section 2: Industry Stakeholders

- How challenging do you find compliance with AQMP standards?
- What are the key barriers preventing compliance in your sector?
- How frequently does your company monitor emissions?
- How well does the AQMP address industrial concerns?

- What benefits, if any, have you observed from AQMP compliance?

Section 3: Community/NGOs

- How aware are you of the AQMP?
- How would you rate the current air quality in your area?
- What do you perceive as the main pollution sources?
- How often do you experience health issues possibly linked to air pollution?
- How effectively does the AQMP respond to community concerns?
- Have you ever raised air quality complaints to authorities?
- How satisfied are you with responses to complaints?

8.2 Appendix B: ANOVA Statistical Analysis

This appendix summarizes the statistical analysis undertaken using a one-way Analysis of Variance (ANOVA) to test for significant differences in pollutant concentrations across monitoring stations and seasonal cycles within the WBPA.

Objective: To determine if mean pollutant levels varied across locations or seasons.

Key Results:

- SO_2: Significant differences were detected across stations ($F = 6298.03$, $p < 0.001$) and seasons ($F = 107.73$, $p < 0.001$).
- NO_2: Differences were also significant across stations ($F = 5169.85$, $p < 0.001$) and seasons ($F = 151.71$, $p < 0.001$).
- $PM_{2.5}$ and PM_{10}: Both pollutants showed highly significant spatial and seasonal variations (all p-values < 0.001).

These findings indicate notable variation in air quality depending on both location and seasonal conditions.

8.3 Appendix C: t-Test Results – Before vs. After AQMP Implementation

This appendix provides outcomes of independent sample t-tests comparing average pollutant concentrations before (2013–2018) and after (2019–2023) AQMP implementation.

Pollutant	Comparison Periods	t-Statistic	p-Value	Interpretation
SO_2	Before vs After AQMP	21.60	<0.001	Significant increase
NO_2	Before vs After AQMP	56.65	<0.001	Significant increase
$PM_{2.5}$	Before vs After AQMP	-45.66	<0.001	Significant reduction
PM_{10}	Before vs After AQMP	-57.80	<0.001	Significant reduction

Significant differences were observed for all pollutants, supporting improvements in SO_2 and particulate matter levels following AQMP interventions.

8.4 Appendix D: Summary of Pollutant Exceedances at Monitoring Stations

This appendix compiles exceedance frequencies for PM_{10}, SO_2, and NO_2 at key monitoring stations during the study period.

Station	PM_{10} (Annual Avg)	SO_2 (Daily Max)	NO_2 (Annual Avg µg/m³)
Lephalale	55 µg/m³	Exceeded >10 times/yr	42 µg/m³
Mokopane	60 µg/m³	Exceeded 7 times/yr	35 µg/m³

Station	PM_{10} (Annual Avg)	SO_2 (Daily Max)	NO_2 (Annual Avg µg/m³)
Thabazimbi	48 µg/m³	Rare exceedance	31 µg/m³

These exceedances highlight persistent non-compliance with ambient air quality standards across WBPA monitoring locations.

8.5 Appendix E: Spatial Heatmap Generation and Troubleshooting

The Python code used to generate the heatmaps follows standard academic programming practices and is available upon request from the author. Interested readers or evaluators may contact the author to obtain a copy of the code for verification or replication purposes. The full Python script used for spatial heatmap generation is available as a supplementary file on request.

8.6 Appendix F: Ethics Clearance Documentation

The University of the Witwatersrand School of Geography, Archaeology and Environmental Studies Ethics Committee (Non-Medical) granted the following ethics clearance unconditionally.

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

SCHOOL OF GAES ETHICS COMMITTEE
CONSTITUTED UNDER THE UNIVERSITY HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)

CLEARANCE CERTIFICATE	**PROTOCOL NUMBER:** [redacted]
PROJECT TITLE	EVALUATION OF THE IMPLEMENTATION OF THE FIRST-GENERATION WATERBERG-BOJANALA PRIORITY AREA AIR QUALITY MANAGEMENT PLAN (AQMP)
INVESTIGATOR	Victor Loate
SCHOOL/DEPARTMENT OF INVESTIGATOR	Geography, Archaeology and Environmental Studies
DATE CONSIDERED	27 September 2024
DECISION OF THE COMMITTEE	Approved unconditionally
RISK LEVEL	MINIMAL RISK
EXPIRY DATE	Date of submission of the Research Report

ISSUE DATE OF CERTIFICATE: 01 October 2024

(Dr M Mvimi)

cc: Supervisor: Prof Mary Evans

DECLARATION OF INVESTIGATOR

To be completed in duplicate and **ONE COPY** returned to the Chairperson of the School/Department ethics committee.

I/we fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to ensure compliance with these conditions. Should any departure be contemplated from the research procedure as approved, I/we undertake to submit an amendment of the protocol to the Committee.

Signature **Date**

PLEASE QUOTE THE PROTOCOL NUMBER ON ALL ENQUIRIES