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Contents

Commentary

News

Research brief

Book review

Research articles

Commentary

Decarbonization of Africa: Metamorphosing the continent for sustainable trajectories

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Introduction

In Africa, the well-being of individuals has been considerably enhanced over the years due to significant economic growth as a result of speedy digitalization, industrialization, urbanization, and technological advancements and innovations (Shoo et al., 2022). Low-income countries in sub-Saharan Africa have emitted fewer greenhouse gases than high-income countries. However, it is crucial to take immediate action toward identifying sustainable approaches for decarbonizing Africa (Collett and Hirmer, 2021). Currently, Africa's land and oceans are experiencing a faster rate of warming than the global average. The Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report indicates that critical levels of global warming are likely to be attained earlier than mid-century in Africa due to the continent's high susceptibility to climate variability and change. Africa is at risk of the adverse impacts of climate change that can affect the health and well-being of millions of people (Ayugi et al., 2023).

Human activities have had a growing impact on the temperature and climate of the earth since the time of the Industrial Revolution. Activities such as deforestation, expansion of livestock cultivation, and combustion of fossil fuels are generating significant quantities of gases that are released into the atmosphere. The continual emission of gases from these activities leads to an increase in the greenhouse effect, causing global warming. Despite the benefits of economic growth, it has also caused a significant rise in CO_2 emissions, environmental degradation, and loss of biodiversity, with some of these negative impacts taking several decades to undo, while others may be irreversible (Omotoso and Omotayo, 2024).

The African Union developed the African Agenda 2063 in 2013, outlining 17 Sustainable Development Goals (SDGs) for the continent with an emphasis on partnerships, environmental preservation, and human well-being. The 2063 Agenda acknowledges the link between inequality, poverty, unemployment, and energy poverty, and seeks to investigate the relationships among these objectives while comprehending global development norms and practices (Garfias Royo et al., 2022). To resolve this issue, strategic approaches would be implemented to create an inclusive and sustainable energy supply system with minimal environmental impact. The approach of decarbonization is a major means of achieving this goal, especially in light of the outcomes of the UNFCCC at the 26th Conference of Parties (COP26) (Momodu et al., 2022). The shift to a low-carbon future in Africa requires the decarbonization of energy and other systems. There is an imperative need to decarbonize Africa to reduce the adverse impacts of GHG emissions on the environment as well as on human lives and well-being (Miralles-Quirós and Miralles-Quirós, 2022). Therefore, this commentary seeks to briefly address the challenges and pragmatic approaches to achieving the decarbonization of Africa.

Challenges to the decarbonization of Africa

The decarbonization of Africa encompasses many challenges, of which difficulties in the incorporation of highly renewable energy are major challenges, which are often grouped into economic, social, and technological challenges. The key priority in addressing this challenge is to guarantee that technological solutions will be made accessible on a large enough scale and at a reasonable cost, particularly for industries that are harder to transition to lower carbon emissions (Fay et al., 2015). There is inadequate consideration given to these system integrations and the social and non-financial aspects when addressing decarbonization in Africa. Also, the primary economic challenge is seen as the requirement for significant investments in low-carbon technologies within the energy sector, in both developed and developing nations (Papadis and Tsatsaronis, 2020). There is an absence of pledges at each national level to pursue decarbonization pathways, coupled with little to no policies and financing options that support both decarbonization and economic growth in the long term (Moreno et al., 2024). This is no longer surprising in Africa, as both domestic and global political efforts have fallen short of meeting the set target for decarbonization. A contributing factor to this lack of significant action on climate change globally and in Africa is the need for upfront investments in transitioning to zero-carbon electricity and transportation, and this is a major barrier for almost all African countries. Another obstacle is the significant distributional effects on employment that will ensue, both within countries and across the continent, with millions of jobs lost in the process (Strauss and Derviş, 2021).

The challenge of technical issues will pose a barrier to the decarbonization of Africa, and less developed nations may also encounter various technological issues in the practice of the technologies to reduce GHG. These issues may even persist more in less developed countries in the proper disposal of waste and the sustained functioning of different specific renewable energy technologies after the departure of foreign experts. The establishment and expansion of renewable energy sources will be impeded in many developing countries in Africa due to a lack of well-defined energy policies and insufficient legal and organizational capabilities (Manda, 2020; Okoh and Okpanachi, 2023; Santos et al., 2022). Decarbonization also poses various challenges encompassing financial, technical, economic, and social factors to a company's growth and development in Africa, which, in the long run, weaken the already weak economies of many African countries.

Pragmatic approaches to decarbonization of Africa

It is imperative for the government and concerned agencies in Africa to scale up their efforts to drive the development and deployment of renewable energy technologies through the implementation of financial incentives and strategic partnerships. This includes prioritizing investment in large-scale renewable energy projects and distributed energy systems like rooftop solar panels (Masson et al., 2014). Public awareness campaigns should be implemented to educate people about the benefits of renewable energy and the urgency of transitioning away from fossil fuels. By taking these actions, Africa can make significant progress toward building a more sustainable future and reducing dependence on fossil fuels (Masson et al., 2014). In the quest for decarbonization, enhancing energy efficiency is vital to reduce energy consumption and mitigate climate change's negative impacts. The International Renewable Energy Agency (IRENA) must play a leading role in developing policies that promote energy efficiency across various sectors, establish standards, and provide financial incentives for energy-efficient upgrades. Increased research and public awareness campaigns are crucial in this regard, leading to substantial cost savings and environmental benefits (Oyedepo, 2012).

To advance sustainable transport and reduce greenhouse gas emissions, African governments should invest in public transportation systems like buses and light rail to encourage people to use public transport instead of private vehicles (Okesanya et al., 2024a). Also, promoting electric vehicles (EVs) through charging infrastructure and alluring benefits in the form of tax credits, rebates, and subsidies will not only reduce emissions but also improve air quality (Manda, 2020). Enhancing energy efficiency and sustainability in buildings also requires African governments and relevant authorities to offer incentives for builders, implement green building standards and certifications, raise public awareness, and establish regulations for new constructions to meet energy efficiency criteria. These actions encourage the adoption of cost-effective and environmentally friendly practices and technologies (Gai et al., 2020; Røstvik, 2013). African countries can foster sustainable agriculture and forest conservation by supporting sustainable farming practices, encouraging afforestation and reforestation efforts, funding research and development, and raising public awareness. These actions can reduce emissions, promote soil health, increase productivity, and sequester carbon (Liu et al., 2021). Providing aid, technical assistance, training to farmers, public engagement, research development and funding, and implementing policies for environmental conservation can all contribute to creating a more sustainable future (Liu et al., 2021). Furthermore, to improve access to clean cooking solutions, there is an urgent need to develop policies that promote eco-friendly and efficient cooking technologies, provide access to clean cooking fuels, and launch public awareness campaigns. Offering subsidies and tax incentives can make clean fuels more affordable and accessible to low-income households (Welle, 2023). Promoting public education on the benefits of clean cooking solutions and the negative impacts of traditional methods can encourage households to switch, which is crucial for public health, greenhouse gas emissions reduction, and climate change mitigation.

The governments, policymakers, and relevant authorities in Africa can promote international cooperation and financing for clean energy projects and decarbonization initiatives by strengthening partnerships, mobilizing climate finance, and prioritizing supportive regulatory frameworks. Africans must seek collaborations with international organizations, multilateral development banks, and the private sector to mobilize funding for clean energy projects and decarbonization. Lastly, they should create supportive regulatory frameworks that incentivize private sector investment in clean energy and decarbonization (African Development Bank, 2021).

The African Assessment is a crucial tool in guiding actions towards mitigating climate change across Africa. It uses modeling approaches like SEI's Low Emission Analysis Platform and NASA's global composition and climate model to provide detailed insights into the impact of short-lived climate pollutants (SLCPs) on African climate and air quality (United Nations Environment Programme [UNEP], 2022). The Assessment identifies feasible pathways for implementing nationally appropriate measures, which have been rigorously assessed and validated by stakeholders. Many African countries are already developing integrated emission inventories and impact assessments based on the assessment's findings to inform their nationally determined contributions. The Assessment's aim is to enhance capacity for short-term and long-term national planning for integrated air pollution and climate change strategies. The development of scenarios, such as the baseline scenario, the SLCP scenario, and the Agenda 2063 scenario, provides valuable insights into future emission trajectories and potential mitigation measures (UNEP, 2022; Okesanya et al., 2024b; Malley et al., 2021).

Conclusion

The decarbonization of Africa presents numerous challenges, including economic, social, technological, and political barriers. However, the implementation of pragmatic approaches such as expanding renewable energy sources, enhancing energy efficiency, promoting sustainable transport and buildings, supporting sustainable agriculture and forest conservation, improving access to clean cooking services, and fostering international cooperation will be significant in creating sustainable, low-carbon development and a prosperous future for the continent and its people. To this end, it is imperative that immediate action be taken to mitigate the adverse effects of climate change on the African continent.

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Author contributions

All authors have contributed equally to the writing of this article. We have all read and approved the final draft.

Declarations

Conflict of interest: The authors declare no competing interests.

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News

UNEA-6 Resolution on Air Quality acknowledges the Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa

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Clean Air Benefits for Africa

In a major boost to air quality and sustainable development in Africa, a new **UNEA-6 Resolution on Air Quality has acknowledged the Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa**.

The new development came in 2023, when the Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa (UNEP, 2023), was published by a partnership of the African Union, Climate and Clean Air Coalition and the United Nations Environment Programme. The assessment was developed with contributions from over 100 authors across Africa, in a process supported by the Stockholm Environment Institute (Kaudia et al. 2022). The Assessment recommended for an Africa Clean Air Program (ACAP) to provide a key rallying point for African multilateral institutions, the Regional Economic Communities (RECs) and Member States, and development partners to work collaboratively to implement the recommendations from the assessment and deliver multiple benefits of clean air for Africa.

The Assessment recommends a package of 37 measures across five key development areas: transport, residential energy, energy generation and industry, agriculture, and waste management (Figure 1). Seventeen of these 37 measures focus on reducing short-lived climate pollutants (SLCPs) such as methane, black carbon and hydrofluorocarbons. Besides meeting national development goals, implementing these measures can deliver substantial clean air, regional climate and development benefits for Africa by 2030 and 2063, in line with the SDGs and the African Union's Agenda 2063 – the Africa We Want respectively.

The African Assessment clearly demonstrated that action that is both integrated across climate and clean air objectives and coordinated across the five key sectors can potentially deliver:

- Substantial reductions in emissions of greenhouse gases (GHG), including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), SLCPs, including black carbon, ozone precursors and hydrofluorocarbons, and other air pollutants (40-80% by 2063);
- Prevention of 200,000 premature deaths per year by 2030 and 880,000 premature deaths per year by 2063 due to outdoor and indoor air pollution;
- Improving food security by reducing desertification and increasing crop yields for rice, maize, soy and wheat;
- Limiting the negative effects of regional climate change on rainfall, especially in the Sahel region, and temperature in parts of Africa.

Links to the UNEA Resolutions

The sixth United Nations Environment Assembly (UNEA-6), through its 'resolution on promoting regional cooperation on air pollution to improve air quality globally (UNEP 2024)' has now set the scene for accelerating delivery of the Africa Clean Air Program as part of the African Union's Agenda 2063. The Resolution 'Encourages member states to accelerate efforts to implement relevant provisions of Environment Assembly resolution 3/8 on preventing and reducing air pollution to improve air quality globally, including developing national air quality programmes and setting national ambient air quality standards, bearing in mind the most recent air quality guidelines of the World Health Organization, as appropriate in their national circumstances'.

The Integrated Assessment on Air Pollution and Climate Change for Sustainable Development in Africa (UNEP, 2023) has outlined how this can be achieved while simultaneously delivering clean air, regional climate and development benefits in Africa. The UNEA-6 air quality resolution acknowledges 'the progress achieved by existing bodies and initiatives that facilitate cooperation on in-country and transboundary air pollution, including' inter alia the 'Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa and its proposed Africa Clean Air Program'.

The 37 African Assessment measures resonate particularly well with the theme of the UNEA-6 discussions, i.e. 'inclusive and sustainable multilateral actions to tackle climate change, biodiversity loss and pollution,' and actions in the following areas:

- Cooperation with Multilateral Environmental Agreements,
- Implementation of resolution 3/8 on preventing and reducing air pollution to improve air quality globally,
- The implementation of resolution 4/3 on sustainable mobility,
- Implementation of resolutions 4/14 and 5/2 on sustainable nitrogen management,

Figure 1: *Examples of the 37 measures across five key development areas: energy generation and industry, residential energy, agriculture, transport and waste management, recommended by the Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa (Image copyright: Climate and Clean Air Coalition)*

- Implementation of resolution 5/1 on the animal welfare–environment–sustainable development nexus,
- Implementation of resolution 5/7 on the sound management of chemicals and waste,
- Implementation of resolution 5/9 on sustainable and resilient infrastructure,
- Implementing resolution 5/11 on enhancing circular economy as a contribution to achieving sustainable consumption and production.

The links between the benefits of the Africa Assessment's mitigation measures and the aims of UNEA resolutions are clear and include improving air quality, crop yields, animal welfare, sustainable nitrogen management (including circularity of livestock manure), waste management and increased renewable energy, sustainable mobility, and residential energy options.

Tackling air pollution climate change and sustainable development across the scales

The Africa Assessment shows how coordinated action from local/city scales, through sub-national, to national, regional, and continental scales is necessary for achieving national and international targets for air quality, climate change and sustainable development. For example, the importance of the national scale is demonstrated by several countries in Africa that have already included actions related to the Assessment's measures in the Nationally Determined Contributions (NDCs) under the Paris Agreement, although often without reference to specific measures or targets. By demonstrating how the 37 measures deliver against a range of policy objectives and showing that all of these proposed measures are technologically proven and cost-effective, as well as implemented already somewhere on the continent, the case can be made for considering their inclusion into the reviews of the NDCs that are due for submission in 2025. Such inclusion can unlock climate finance to implement these solutions at scale. Using such approaches, the African Assessment shows that action that is both integrated across climate and clean air objectives and coordinated action across multiple sectors can potentially deliver substantial development benefits. The time to act is now.

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From
unwanted
to
wanted

Research brief

Fuel switching and energy stacking in low-income households in South Africa: A review with recommendations for household air pollution exposure research

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Household air pollution (HAP) caused by domestic burning practices for cooking was linked to almost nine thousand deaths in South Africa in 2012 (Roomaney et al., 2022). Domestic burning, as practised by millions of South African low-income households, proves complex and multi-faceted. Fuel use practices are made up of various fuel stacking and switching habits for cooking, heating and lighting (DoE 2012, Shupler et al., 2019). The levels of HAP and related health impacts vary based on factors such as fuel type, duration of use, and combinations of fuels used to meet energy needs. In scenarios where direct HAP measurements are unavailable, detailed information from field surveys on household fuel use patterns can serve as a proxy for HAP exposure, the accuracy of which depends on the quality and extent of the information gathered during the field surveys.

This Research Brief summarises the findings of the review study *Fuel switching and energy stacking in low-income households in South Africa: A review with recommendations for household air pollution exposure research*, which emphasises that when more detailed information is gathered through surveys about fuel use patterns, our understanding of associated HAP exposure improves (Wernecke et al., 2024). Based on the findings of a thorough review study, the paper put forward recommendations for improved questionnaire design for optimized data collection and improved exposure HAP proxy development without physical HAP measurements. These recommendations can be grouped into the following overarching themes:

- Context-specific data collection: Tailor data collection to reflect the specific spatial and temporal contexts of the surveyed households.
- Longitudinal and comprehensive analysis: Include analyses of all fuel types used within households, not just the primary fuels.
- Economic and behavioural factors: Consider the economic dynamics and behavioural factors influencing fuel use, including access to and availability of various fuels.
- Integration of cultural and sensory factors: Incorporate aspects of cultural preferences, perceptions, and demographics to understand fuel choice motivations.

Adopting these recommendations would lead to more effective interventions and policies aimed at reducing HAP and improving health outcomes in vulnerable populations. The study ultimately calls for an integrated approach that combines quantitative and qualitative data to provide a more comprehensive understanding of the impact of fuel use on air quality and health. While this study focused on South African households, the findings and recommendations are applicable to similar contexts globally, particularly in regions where low-income communities face similar HAP and health challenges.

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Book review
Sustainability of Southern African Ecosystems under Global Change

Review by Jenifer Veitch, Guy Midgley, Gregor Feig and Graham Von Maltitz

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In this book review, we provide a summary of some key and relevant findings of the recently published, open access, book entitled: 'Sustainability of Southern African Ecosystems under Global Change: Science for Management and Policy Interventions' (von Maltitz et al (2023)).

The book is a compilation of chapters that are the outcome of German – African collaborations under the auspices of the German Federal Ministry of Education and Research (BMBF)-funded SPACES II project (2018-2022). Reference: von Maltitz, G., G.F. Midgley. J. Veitch, C. Brümmer, R.P. Rötter, F.A. Viehberg and M.Veste (eds) (2024) *Sustainability of Southern African Ecosystems under Global Change: Science for Management and Policy Interventions*, Ecological Studies, Volume 248, Switzerland, Springer. Link: https://link.springer.com/book/10.1007/978-3-031-10948-5

The book highlights the profound impact of climate change on Southern African ecosystems by examining regional climate trends and extreme weather events and their consequences for biodiversity, agriculture, and water resources. All of which have an impact on air pollution and atmospheric composition. The scientific insights provided support the adaptation and mitigation strategies that are required to address these challenges. The book highlights the urgency of adopting sustainable practices and policies, along with integrated approaches, to mitigate the adverse effects of climate change on the southern African region.

Key drivers of terrestrial ecosystems are examined, such as land-use changes, biodiversity loss, and climate variability impacting these ecosystems. The contributors discuss current research findings that shed light on the intricate relationships between vegetation, soil, and climate. Marine ecosystem issues addressed include overfishing, habitual degradation, and the impacts of climate change on ocean processes, as well as how they contribute to atmospheric variability. This body of work underscores the fact that the sustainability of both marine and terrestrial ecosystems in the Southern African Region depends strongly on science-based strategies for their management and conservation.

Providing tools for the development of effective policies for the sustainable management of Southern African ecosystems, as well as to support societal resilience, are overarching objectives of the collection of chapters in this book. To this end, existing policies and gaps are analysed and science-based interventions to support more sustainable approaches are proposed. Additionally, it examines how Southern African communities adapt to shifting ecological conditions and emphasizes the need for inclusive and participatory approaches. The role of education, community empowerment, and sustainable development are highlighted as integral in enhancing societal resilience. The book emphasizes the importance of interdisciplinary collaboration, community engagement, and adaptive management approaches in crafting new policies that balance ecological conservation with human needs.

While the focus of this book is not the atmospheric community there are valuable lessons to be learned. This book highlights the complexity of environmental research on the African continent in its surrounding oceans and illustrates the importance of an integrated approach when designing and implementing policy.

Research article

Identifying critical assumptions and risks in air quality management planning using Theory of Change approach

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Abstract

Governments across the world have been developing legislation and policy implementation instruments to address air pollution issues. Air Quality Management Plans (AQMPs) have emerged as a key instrument, with most developed countries having established effective AQMPs. These take a variety of forms depending on the overarching national framework for environmental regulations. The uptake of AQMPs in low and middle-income countries, however, has been less broad and, even in those that have adopted AQMPs, their effectiveness and efficiency have been limited, especially in urban areas. South Africa has adopted AQMPs and is recognised as having one of the most mature and complex air quality management legal frameworks in the world. Yet South Africa is still facing serious air quality challenges, especially in those areas that have been declared as priority areas. This paper, therefore, aims to identify critical assumptions and risks as a basis to evaluate the effectiveness of AQMPs as a policy instrument through the application of Theory of Change (ToC) approach. This study has resulted in the development of the ToC map, identification of 15 critical assumptions and associated causal narrative framework. In addition, this paper identified key risks underpinning the AQMP development and implementation process in South Africa. The identified critical assumptions embedded within different components of the ToC framework are not the only assumptions relating to this policy instrument, however, they are the fundamentally important ones that may significantly impact the success or failure of the AQMP system in South Africa if not managed. This study suggests that in order to further understand the challenges relating to the effective development and implementation of AQMPs, it is important that further research be conducted to test the validity of these critical assumptions which will provide solutions towards avoiding or mitigating risks associated with them.

Keywords

Air Quality Management Plan (AQMP), Critical Assumptions, Theory of Change (ToC), Narrative. Map, Risk, Development and Implementation Process.

Introduction

Air is one of the most important environmental parameters in which all forms of life on Earth depend for survival in that it plays a vital role in several key processes that support life such as providing oxygen (O_2) for humans and organisms respiration (Imray et al., 2003). However, due to the human activities that introduce pollutants into the atmosphere, the ambient air quality has been gradually deteriorating over the years and has now become a major global human health, climate change, and environmental concern (Cohen et al., 2017; Roomaney et al., 2022; Sinha, 2018). Urban air pollution, and air quality impacts in particular, are a worldwide problem that affects different regions in different manners depending upon various aspects such as politics, economy, and technological landscapes of each particular region or country as well as on the nature of the available energy sources (Sinha, 2018). Rapid population growth, urbanisation, and industrialisation in recent decades have increased the introduction of air pollutants in the atmosphere which are associated with a range of acute and chronic effects on human health (Afros et al., 2003). Studies have found a direct correlation between emissions of carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x), ozone (O_3), toxicants, and particulate matter (PM) with public health implications in both developing and developed countries (Dugard, and Alcaro, 2013; Henneman et al., 2016; Sinha, 2018). PM_{10} is all particulate matter less than 10 micrometres in diameter, within which fine particulate matter $PM_{2.5}$ is a subcategory of less than 2.5 micrometres in diameter. According to Southerland et al., (2022), majority of the world's population was found to be living in territories with harmful $PM_{2.5}$ concentrations between 2000 and 2019 translating to non-communicable disease burdens. According to the World Health Organization (WHO) 2016, approximately 91% of the world's population is living in areas where air quality levels exceed WHO limits. More to this, WHO indicates that seven million people die prematurely each year because of polluted air of which 600 000 are children under 5 years old. Poor air quality is the third leading cause of death after heart disease and smoking globally.

As a means of regulating air pollution and related impacts, governments in many countries have been developing legislation and policy implementation instruments to regulate and manage activities that contribute to air pollution (Kuklinska, et al., 2015; Mukwevho et al., 2022; Sheikh, 2020).

One of the widely adopted policy instruments is air quality management plans (AQMPs) (Feng et al., 2019; Gulia et al., 2015; Sivertsen and Bartonova, 2012; Gokhale, and Khare, 2007; Engelbrecht, and VD Walt 2007; Lieu, and Treyz, 1992; Miranda et al., 2015, Moreoane et al., 2021; Park, and Bae, 2006). These plans are defined as strategic instruments that describe past trends, the current state of air quality in a city or region and stipulate goals and objectives and describe short and long-term strategies, policies and controls to improve air quality within a city or region (Sivertsen, and Bartonova, 2012; DEA, 2012). Different countries use different terms to describe AQMPs such as air quality plans (AQP) (European Union member states), urban air quality management plans (UAQMPs) (e.g. India, UK, USA), air pollution prevention and control action plan (the action plan) (e.g. China) (Feng et al., 2019; Gulia et al., 2015, Sivertsen, and Bartonova, 2012; Gokhale, and Khare, 2007; Engelbrecht, and VD Walt 2007; Lieu, and Treyz, 1992; Miranda et al., 2015; Moreoane et al., 2021, Park, and Bae, 2006). The use of these terms depends on the spatial scale of a region which varies from national level, city level and site-specific level. An AQMP, therefore, provides measures, strategies, or interventions that will achieve air quality goals and objectives of a particular geographical area and for it to succeed it requires the involvement of various stakeholders from government, business, industry, non-profit or non-government organisations (NPOs or NGO's) (Sivertsen, and Bartonova, 2012). Governments must therefore prioritise air quality management and the development and implementation of efficient AQMPs as a key policy tool is needed to protect public health and preserve the environment.

Many developed countries such as USA, UK, and Australia have managed to develop and implement their AQMPs at different scales in accordance with their regulatory management frameworks (Gulia et al., 2015; Gulia et al., 2020; Sivertsen, and Bartonova, 2012; EEA, 2008; Tonne et al., 2008; Hasheminassab et al,. 2014). Recent studies suggest an improvement in some of the air quality parameters such as $PM_{2.5}$ and PM_{10} concentrations in countries such as China, Korea, Japan, Spain, United Kingdom (UK) and Europe particularly at the regional or city level (Colette et al., 2020; De la Campa et al., 2018; Ito et al., 2021; Munir et al., 2021; Sicard et al., 2021). These improvements are the results of various policy interventions associated with their AQMP implemented by those countries in recent years. Cities including Paris, Sao Paulo, Mexico City, and New York have managed to address their vehicular emissions by implementing their AQMPs focusing on circulation restriction, fuel initiatives, technological advancements such as emission abatement technologies as well as fiscal incentive approaches in targeting fuel and technology initiatives (de la Campa et al., 2018; Slovic, and Ribeiro, 2018; Molina et al., 2019). Some trends emanating from megacities of these countries show that urban air quality does show signs of improvement as a result of proper implementation of AQMPs (Gulia et al., 2015; Gulia et al., 2020; Naiker et al., 2012). This was seen in the European Environment Agency (EEA) countries where vehicular emissions were shown to be significantly reduced from 1990 to 2009 for SO_2, NO_x, PM_{10} and $PM_{2.5}$ (Gulia et al., 2015). Significant reductions of NO_2 were observed in Cardiff and Norwich cities after a successful implementation of UAQMP (Moorcroft, and Dore, 2013). Correia et al., (2013), found that efficient and effective implementation resulted in the reduction of $PM_{2.5}$ which led to an increase in life expectancy in 545 counties in the USA.

In contrast, low and middle-income countries have typically not yet been able to efficiently and effectively implement their AQMPs, particularly at regional or city level such as Beijing , Shanghai, Guangzhou, and Chongqing in China, and New Delhi, Mumbai, Calcutta in India, as well as in Priority Areas in South Africa. This is mostly due challenges such as poor regulator and stakeholder commitment and participation, weak legal framework and poor quality of air quality data and emission inventories among other things (Tshehla, and Wright, 2019; Gulia et al., 2015; Gulia et al., 2020; Naiker et al., 2012; Groundwork, and VEM, vs. minister of environmental affairs case, 2022). This has since prompted several studies to be conducted globally over the past few years to evaluate the effectiveness of environmental policy regulations and instruments including air quality interventions (Feng et al., 2019; Shakil, and Ananya, 2015; Wang et al., 2014; van Erp 2008; Retief et al., 2011; Jorquera 2021).

South Africa case example

Like many other countries, an AQMP in South Africa is a legal requirement in terms of the National Environmental Management Air Quality Act (NEM: AQA) no 39 of 2004. This Act requires each national department, province, and municipality to prepare and implement an AQMP. The Act further requires that those organs of state that prepare the AQMP must also report on the plan's implementation. The NEM:AQA further requires that once the AQMP is developed, the national and provincial environmental departments must incorporate the AQMP into other sector plans such as environmental management plans (EMPs) and environmental implementation plans (EIPs) which are required in terms of the National Environmental Management Act (NEMA) framework legislation (Naiker et al., 2012). Municipalities are also required in terms of the Municipal Systems Act 32 of 2000 to include an AQMP in the Integrated Development Plan (IDP) which is the municipal strategic planning document.

Despite having established AQMP as an approach within one of the world's most mature and complex air quality management legal framework (Mukwevho et al., 2022; Nel, and Alberts, 2018), South Africa is still facing serious air quality challenges relating to air pollution, especially in those areas that have been declared as priority areas (September 2012; Tshehla, and Wright, 2019). In addition, according to the Department of Forestry, Fisheries and Environment (DFFE, 2021a) since the promulgation of NEM: AQA in 2004, not all municipalities and provinces have successfully developed and implemented AQMPs with 34 of 44 district municipalities, 7 out of 8 metropolitan municipalities, and 7 out of 9 provinces having developed AQMPs in 2020 (DFFE 2021a; Tshehla, and Wright, 2019). Given this lack of AQMP development and implementation, a better understanding is required of the underlying challenges. This is typically achieved through policy instrument evaluations and identifying constraints including underlying assumptions and risks that underpin the design and implementation of the particular policy instrument (Mason, and Barnes, 2007; Vogel, 2012; Alberts et al., 2020). The latter has not been done in relation to AQMP in the South African context which then makes it a good case study for global lessons.

This paper, therefore, aims to identify critical assumptions and risks as a basis to evaluate the effectiveness of air quality management planning system through the application of the Theory of Change (ToC) approach. Like in other governance instruments, identifying and evaluating assumptions and risks is crucial to ascertain whether the system operates as intended or if there are flaws in its design (Moolman et al., 2022). If the latter scenario occurs, it becomes imperative to re-evaluate the system's design by means of policy and legislative reform (Moolman et al., 2022). We propose using ToC approach in identifying critical assumptions because it will provide the basis for further performance evaluation on the effectiveness of AQMPs which is a crucial step toward understanding the issue of poor development and implementation of AQMPs in South Africa and perhaps other countries.

Theory of Change (ToC) method of evaluation

Evaluation research under the term theory of change evaluation has been applied previously in assessing the effects of various social programmes and has also recently been applied to governmental programmes including important evaluations of job training programmes, compensatory education, mental health centres, community health services, community action, law enforcement, corrections, and other government interventions (Alberts et al., 2021; Amundsen, and D'Amico, 2019; Archibald et al., 2016; Biggs et al., 2017; Connell, and Kubisch, 1998; Jackson, 2013; Thornton et al., 2017; Weiss, 1995). According to Biggs et al., (2017), ToC can be defined as an instrument that supports decision making by identifying the causal relationships and sequences of the events required for a programme to reach its intended outcomes and describing the key assumptions in each step of the process. ToC evaluation's interest is to apply logical thinking to reconstruct a causal model based on several sources to unpack how a specific intervention (programme) is intended to achieve its outputs and outcomes based on its inputs and activities (Stame, 2004; Rogers, 2008).

Theory of change approach exposes the assumptions underpinning how policy instruments are expected to function (Alberts et al., 2022; Alberts et al., 2021; Moolman et al., 2022; Amundsen, and D'Amico, 2019; Connell, and Kubisch, 1998; Vogel, 2012). Connell, and Kubisch, (1998), earlier described ToC as a systematic and cumulative study of the links between activities, outcomes, and contexts of the policy instrument by specifying how activities will lead to interim and longer-term outcomes and identifying the contextual conditions that may affect them. Furthermore, through ToC approach, assumptions are identified through a systematic process that also requires agreement between relevant stakeholders and practitioners in the particular field of interest and this approach has been recognised as a best practice performance evaluation method (Allen et al., 2017; Alberts et al., 2021; Connell, and Kubisch, 1998; Davidson, 2005; Stein, and Valters, 2012).

Internationally, several programmes including community-based development programmes have also used ToC, with many international agencies considering ToC as a best practice evaluation method (Allen et al., 2017; Archibald et al., 2016; Biggs et al., 2017; Connell, and Kubisch, 1998; USAID, 2015). In addition, ToC approach was selected for this research due to its wide adoption as a policy evaluation method and its status as a mandated policy evaluation method in South Africa (Moolman et al., 2022; Alberts et al., 2022; Alberts et al., 2021; DPME 2011).

According to Brookfield (1995), assumptions are perceived as beliefs, expectations, or considerations taken for granted about how the world works. Assumptions play a vital role in the success of any programme and so in order to design a project with a good chance of success, there is a need to have consensus among the project designers on what they expect to be true in order to determine any gaps in the logic of the project and assess whether an assumption will, in fact, turn out to be valid or true (Nkwake, 2013; Kaplan, and Garrett, 2005, Weiss, 1995). Assumptions may be valid or invalid and there may only be a few that are critical among the many assumptions underpinning an intervention or a programme (van Es, and Guijt, 2015). This means that if these assumptions are not valid or true, the intervention will probably not work as planned and therefore it is essential to identify which assumptions are most critical to the success of the intervention (van Es, and Guijt, 2015). These assumptions also pose risks to the effectiveness of the policy instrument as well as the extent to which it can be expected to achieve its intended outcomes (Moolman et al., 2022; Archibald et al., 2016; DPME 2011). Accordingly, this paper aims to identify critical assumptions and risks to the effectiveness of AQMP development and implementation in South Africa through the application of ToC.

Methodology

Overview

This study adopted a method used in several international and local studies in applying the ToC approach to identify critical assumptions and risks to the AQMP system as a policy instrument in South Africa (Alberts et al., 2022; Durant et al., 2022; Moolman et al., 2022; Alberts et al., 2020; Alberts et al., 2019; Archibald et al., 2016). The application of the ToC approach allows for an existing policy instrument to be broken down by critically analysing and understanding the causal linkages of all the steps involved in the development and implementation of that policy instrument (DPME, 211).

This is then presented in the form of a causal narrative and visual ToC map (Figure 2). The South African AQMP development and implementation system is broken down into six different ToC components (i.e. design, inputs, activities, outputs, outcomes (immediate and intermediate), and impacts following the ToC approach of other key studies (Alberts et al., 2022; Moolman et al., 2022; Alberts et al., 2022; Thorton et al., 2017; DPME 2011; Weiss, 1995; Stein, and Valters, 2012; Romero, and Putz, 2018). These ToC evaluation components are generally conceptualised and designed based on the so-called results-based pyramid (Alberts et al., 2022; Moolman et al., 2022; Alberts et al., 2021; DPME, 2011).

The results-based pyramid illustration provides the key questions asked in each of the six components of the ToC framework and this results-based pyramid is adapted in this study for the evaluation of the AQMP policy instrument as shown in Figure 1. The ToC developmental steps (outlined in steps 1-7 below) were conducted based on the results-based pyramid questions which then informed the conceptualisation and development of the ToC map and their causal narrative.

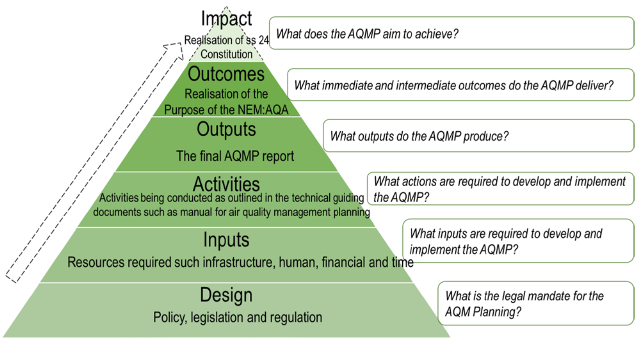

Figure 1: *ToC results-based pyramid for the AQMP process as adapted from the DPME, 2011 and Alberts et al., 2021.*

Development of the ToC map and causal narrative:

Theory of Change for any policy instrument needs to be done through agreements with relevant stakeholders and practitioners in that field to unpack the complexity of such an instrument (Allen et al., 2011; DPME 2011). This was achieved in this study through workshops with stakeholders in which presentations were made by the researchers and questions from the results-based pyramid (Figure 1) were posed. This was followed by feedback sessions where stakeholder participants provided inputs on the ToC map and identified assumptions. Criteria for stakeholder selection were based on experience, knowledge, and direct involvement in at least one of the South African AQMP process. The following steps were followed (full inclusion criteria and workshop details given in Appendix 1):

Step 1: South African Specialist Workshop: The very first ToC conceptual map (see Figure 2) and key assumptions were developed in a workshop with five internal specialists at the North-West University (NWU) who are well-established in the application of ToC methodology to various sectors of environmental management. The initial conceptual ToC map was developed by brainstorming how the AQMP development and implementation process works as required by the legal framework of South Africa. Each step of the AQMP process was critically analysed, broken down and aligned with the six components of the ToC approach (i.e., design, inputs, activities, output, outcome and impact). Once the map had been agreed upon, the key underlying assumptions were identified for each of the six components. The AQMP ToC map and key assumptions were identified and developed by brainstorming based on the specialists' understanding of the South African air quality management and overall environmental legal framework. These participants were expert researchers and consultants in the application of ToC approach and other methodologies to policy evaluations in different disciplines of environmental sciences and management, including environmental impact assessments (EIAs), environmental auditing, water quality, and waste management. Together they had a combined experience of more than 50 years in the field of environmental management and sciences (Alberts, 2020; Alberts et al., 2019; Alberts et al., 2021; Moolman et al., 2022).

Step 2: Academics, consultants, and industry practitioners' workshop: Following the internal specialist workshop, three separate workshops were held during which the conceptual ToC map and the key assumptions were presented to different consultants and practitioners, including scientists, researchers, and practitioners in the industry (consulting firms, state-owned entities, mining, etc.) as shown in detail in Appendix 1. The following workshops were held: (1) Academics workshop with two senior lectures from well-recognised institutions in South Africa, (2) Specialist/consultant workshop with five senior environmental consultants from private consulting firms, (3) Industry workshop with five environmental practitioners/ officers from well-recognised organisations. The attendees were asked questions from the pyramid and were also asked whether they agreed with the assumptions presented to them and if they had anything to add. These participants were selected based on their knowledge, experience, and/or involvement in some part of AQMP development and/or the implementation process, either from a research, consultation, or monitoring and compliance point of view. The comments and additional assumptions from these workshops were then used to further refine the ToC map and assumptions. Some of the comments and assumptions raised in these workshops included issues related to the implementation of the AQMPs.

Step 3: Regulator workshop: Following the consultants' and practitioners' workshops, the ToC map and assumptions were presented to regulators represented by 11 government officials for refinement and to obtain a regulator's input. Representatives from various spheres of government were invited, including national, provincial, and local departments and municipalities (including the Department of Forestry, Fisheries and the Environment (DFFE), Gauteng Department of Agriculture and Rural Development (GDARD), City of Johannesburg; Knysna local municipality, Limpopo Department of Economic Development, Environment and Tourism (LEDET). Each of these officials had experience in the development and/or implementation of an AQMP as a regulator and many of the comments and assumptions raised in the workshop included concerns about the transparency of the AQMP legal framework and issues related to development and implementation.

Step 4: General stakeholder discussions: These engagements were conducted following the input from the previous workshops. Participants in these discussions included three members of non-profit organisations (i.e., Vaal Environmental Justice Group (VEJA) and Vukani Environmental Justice Movement in Action). These organisations are active and influential environmental justice organisations in the Vaal Triangle Airshed Priority Area (VATAPA) and Highveld Prioty Areas (HPA) which are among the air quality priority areas in South Africa.

Step 5: To ensure a broader perspective on the history of air quality legislation in South Africa and from a global point of view, a meeting was held with an ex-government official who had been involved in the initial development of air quality legislation and guidelines in South Africa and is now based abroad. They provided some background on the development of NEM:AQA. This provided valuable context for fine-tuning the design component of the ToC as it relates to how the South African air quality legislation is structured and its intent for AQMP development and implementation.

Step 6: National Association for Clean Air (NACA) Conference. An earlier version of this paper was submitted and presented at the NACA conference on 6–9 October 2021. Several comments and questions were used to further refine the ToC map and assumptions. The paper was also accepted and formed part of the conference papers published online (Mukwevho, and Burger, 2021).

Step 7: UK Air quality professional perspective. In October 2022 a meeting was held with air quality official from the Newcastle-under-Lyme Borough Council to discuss the assumptions and to get a UK perspective on the effectiveness of a UK's air quality action plans.

A ToC can be explained using different methods, such as plain narrative description, causal loop diagrams, logic models and results chains (Senge, 1990; Knowlton and Phillips, 2012). After following the seven steps the development of the ToC map, narrative and identification of critical assumptions, this study went on and conducted a literature review to identify existing literature that corresponds to the identified assumptions. This was done following a similar data collection approach by Mukwevho et al., (2022); and Olagunju et al., (2019), through a broad systematic search of popular academic electronic databases such as Google Scholar, and Scopus. Other non-peer-reviewed literature such as relevant legislations and reports were located from general Google searches, textbooks, and specific databases such as government databases, the Centre for Environmental Rights (CER) library database etc. In doing so keywords were used in the search such as "air quality management plans", "AQMP Assumptions", "South African air quality management", "air pollution risks in south Africa".

At the end of conducting the above steps, the following were the outcomes of the workshops:

- ToC conceptual framework or map (Figure 2);
- causal narrative description as they relate to the 15 key assumptions and;
- their associated risks (see Table 2) underpinning the AQMP development and implementation which are discussed in this section.

Results

ToC map, causal narrative, and critical assumptions

Based on this causal logic this study suggests that the following narrative underpins the AQMP development and implementation process in South Africa which is also summarised in Table 1 and discussed in detail under the Causal Narrative description section:

"The South African AQMP development and implementation process is fundamentally prescribed in legislation (design component). However, for any sphere of government to be able to develop and implement a plan, various resources are required as inputs to the process (input component) and these include time, money, data and information, infrastructure, skills and competencies. In this process, there are six steps to be followed which are prescribed in the manual for air quality management planning guidelines (activity component). An output from the six steps is a detailed final AQMP report (output component) which must be approved, gazetted (only for priority areas) and be incorporated into other sector plans including the IDP, EMP and/or IEP (immediate outcome). Through effective implementation of the intervention strategies in the plan, it is expected that the specific geographic area should be able to meet the National Ambient Air Quality Standards (NAAQS) requirements as well as give effect to the NEMA: AQA requirements (intermediate component). Ultimately over the long run, the AQMP should

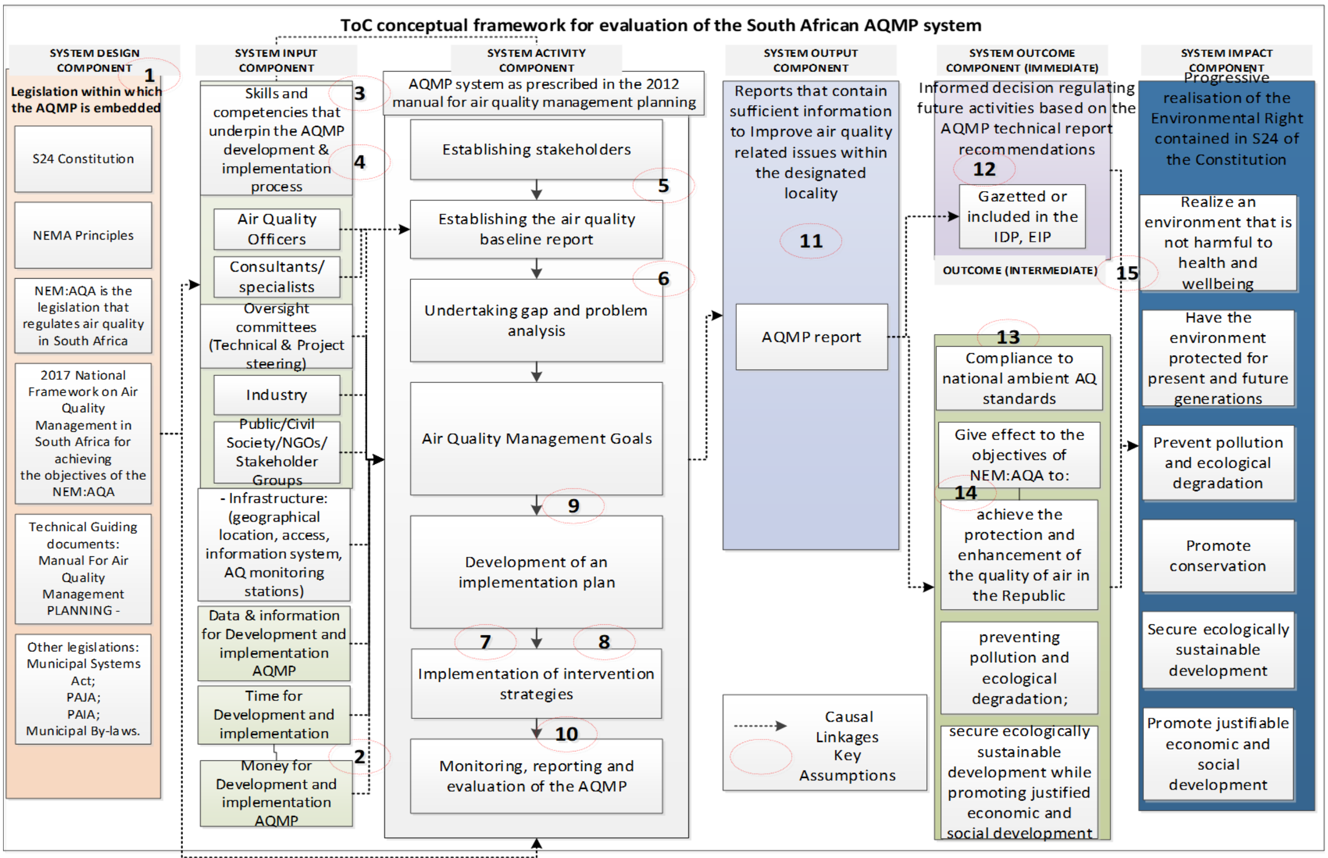

Figure 2: *This figure hows that there are six components that are linked as shown by the black dotted arrows. The red dotted circles indicate the 15 critical assumptions relating to the AQMP development and implementation process in South Africa. These critical assumptions are shown by the red dotted lines and explained in detail in the sections below. A summary of the causal narrative is provided in Table 1 and discussed in detail in the causal narrative description section.*

be able to progressively give effect to the environmental right contained in Section 24 of the Constitution (impact component)."

Causal narrative description

This section provides a further detailed description of the ToC causal narrative of Table 1 and Figure 2 relating to the AQMP development and implementation system:

Design Component

In agreement with various stakeholders, the following critical assumption was identified relating to the design component of AQMP process for South Africa:

- **Assumption 1:** It is assumed that the legislative framework provides guidance towards AQMP development and its implementation.

The ToC map begins with the design component which in terms of the results-based pyramid (Figure 1) is guided by the question "What is the legal mandate of the AQMP development and implementation process?". This component refers to the manner in which the AQMP development and implementation process is prescribed in South Africa by (a) the constitution, (b) NEMA framework legislation, (c) NEM: AQA sector-specific legislation, (d) the national framework for air quality management, (e) technical guiding documents: the manual for air quality management planning, (f) other legislations directly or indirectly informing the process such as Municipal Systems Act, PAJA and PAIA, and (g) Municipal by-laws (see design component in Figure 2).

a. Based on inputs from stakeholders during workshops and a review of existing literature (Naiker et al., 2012; Scorgie, 2012; DEA, 2012, and 2018) this study suggests that the legal and other conditions that inform the process of AQMP development and implementation begin with section 24 of the constitution which provides that the government must use legislative and other means to ensure a human right which is the progressive realisation of an environment that is not harmful to health and wellbeing improve air quality and progressively ensure that ambient air is not harmful to health and well-being by preventing pollution (including air pollution) and ecological degradation. Section 24(b) requires the enhancement of ambient air which will enable an environment that is not harmful to the people of South Africa (Scorgie, 2012).

b. The constitution then translates into the National Environmental Management Act (NEMA) framework legislation in which its purpose is the provision of cooperative environmental governance and provides principles for decision-making on environmental matters (DEA, 2018). Some of the key principles in this act that relate to air quality matters include polluter pays principle, pollution prevention or minimisation as well as the

***Table 1:** Summary of the 6 ToC components as well as what informs each component pertaining to the AQMP development and implementation process in South Africa.*

ToC component stages for AQMP	What informs this component
1. AQMP Process Design: the design components relate to the design of the South African protected area system as reflected and prescribed in	S24 Constitution NEMA principles NEM: AQA sector-specific legislation 2017 National Framework on Air Quality Management in South Africa (also referred to as national AQMP) Technical Guiding documents: Manual for Air Quality Management Planning - Other legislations: Municipal Systems Act; Promotion of Access to Information Act (PAIA) No. 2 of 2000; Promotion of Administrative (PAJA) No. 3 of Justice Act; Municipal By-laws.
2. AQMP Process Inputs: input component for AQMP development and implementation process describes the resources required for the process to be effectively executed	Time Finding/money Data and Information Skills and competencies Human resources: (Air Quality Officers / Consultants / Specialists / Oversight committees (Technical and Project steering) / Industry / Public / Civil Society / NGOs / Stakeholder Groups Infrastructure: (geographical location, access, information system, AQ monitoring stations)
3. AQMP Process Activities There are generally six steps that should be followed to develop and implement an AQMP as prescribed in the 2012 manual for air quality management planning (see Figure 3)	1. Establishment of stakeholder groups, defining the boundaries of the AQMP geographic area and the establishment of a baseline; 2. Gap and problem analysis; 3. Establish air quality goals; 4. Develop interventions and a plan to achieve air quality objectives; 5. Implementation of the intervention strategies; and 6. Monitoring, reporting and evaluation as outlined in the national framework for air quality management planning (DEA, 2012, 2018)
4. AQMP Process Outputs output component are tangible results usually in reports and documents.	Information on stakeholder involvement Baseline report Gap and problem analysis information Draft AQMP Final AQMP
5. AQMP Process Outcomes The outcome component in AQM planning is divided into immediate and intermediate outcomes. The immediate outcome depends on the sphere/level at which the AQMP is done. In declared priority areas, the AQMP must be approved and gazetted by the relevant minister/MEC. AQMPs for municipalities must be included into the IDP/EMP/EIP	Immediate: Gazetted or included in the IDP, EIP Intermediate: • Compliance to national ambient AQ standards (NAAQS) • Give effect to the objectives of NEM:AQA
6. AQMP Process Impact is the realisation of core human rights contained in section 24 of the Constitution	Progressive realisation of the Environmental Right contained in S24 of the Constitution

promotion of participation of all interested and affected parties in environmental governance. Furthermore, NEMA regulations outline the EIA process including public participation that must be followed during the application of atmospheric emissions licences for the listed activities in terms of NEM:AQA

c. The next tier in the design component is the sector-specific NEM: AQA which is the main legislation governing air quality in South Africa. In terms of chapters 3 and 4 of this act, each national department, province, and municipality must prepare an AQMP which is the document that sets out what will be done to achieve the prescribed requirements of NEM: AQA as well as the air quality standard. The objectives of this act are:

To protect the environment by providing reasonable measures for–

i. the protection and enhancement of the quality of air in the Republic;

ii. the prevention of air pollution and ecological degradation; and

iii. securing ecologically sustainable development while promoting justifiable economic and social development; and

To give effect to section 24(b) of the Constitution in order to enhance the quality of ambient air for the sake of securing an environment that is not harmful to the health and well-being of people.

d. In addition to the air quality management plans being prescribed by NEM:AQA, a further detailed description of the development and implementation of AQMPs are outlined in the 2017 national framework for air quality management in the Republic of South Africa which was developed by then the Department of Environmental Affairs (DEA; now DFFE) (DEA 2018). The national framework is considered as the national air quality management plan for the republic and its mandate is to achieve the objectives of NEM:AQA by providing mechanisms, systems, and procedures for the management of air quality in a holistic and integrated manner. This includes the provision of guiding norms and standards relating to all technical aspects of air quality management.
e. The national framework further provides that the development of AQMPs by the various spheres of government must be done in accordance with the process stipulated in the Manual for Air Quality Management Planning published in 2008 and 2012 (henceforth referred to as "the Manual" in this study) (DEA, 2012). The manual for the AQMP development in South Africa was developed and published by then the DEA to guide all spheres of government to establish best practice guidelines on the definition of objectives, strategies, plans, and procedures to meet the requirements of the NEM:AQA on air quality management planning and reporting (DEA, 2012). The Manual aims to improve and harmonise the quality of AQMPs produced by various spheres of government. According to the Manual, six steps need to be followed in the development and implementation of the AQMP as discussed later in the activity component (see Figure 3).
f. There are several other pieces of legislation that directly or indirectly impact on the implementation of the AQMPs (Mukwevho et al., 2022) Such legislation includes the Local Government Municipal Systems Act no. 32 of 2000 which requires that municipalities must incorporate their AQMPs into their integrated development plans (IDP). Other key legislations include the Promotion of Access to Information Act (PAIA) No. 2 of 2000 which relates to the regulation of access to information, including air quality information, although it has provisions for refusing access, as well as the Promotion of Administrative (PAJA) No. 3 of Justice Act, 2000 (effected by section 33 of the constitution) which deals with formal interactions between government departments, the public and other stakeholders by informing due process in decision-making (DEA, 2018). Local municipal by-laws also provide an additional layer towards air quality governance at local level as it is stipulated in section 13(a) of the Local Government: Municipal Systems Act, 2000 (Act No. 32 of 2000).

Input component

The following are the critical assumptions relating to the input component:

- **Assumption 2:** Resources are available to develop and implement the AQMP.
- **Assumption 3:** Cooperative governance exists between government stakeholders.

The input component describes the resources required for the process to be effectively executed (Moolman et al., 2022; Alberts 2020; Alberts et al., 2021; Romero, and Putz, 2018; Thorton et al., 2017; Weiss, 1995). In terms of the results-based pyramid, the key question for the input component, in this case, asks the question "What inputs are required to implement the AQMP?". Once again from the stakeholder engagements, it was evident that key resources required for the development and implementation of an efficient and effective AQMP include data and information, human capacity, skills and competencies, time, money/budget, and infrastructure.

Skills and competencies: According to the "training needs outcomes" from Engelbrecht and van der Walt (2007), and (2012), research papers, the gap regarding technical capacity in municipalities is a matter that requires urgent prioritisation. Some of the key skills and competencies required for the effective development and implementation of an AQMP include air quality modelling, air pollution risk assessment, identification of sources, and emissions quantification (Engelbrecht and van der Walt (2007); Engelbrecht, and van der Walt, (2012)). The required skills and competencies are associated with the main role players and entities required including air quality officers (AQO), consultants/specialists, oversight committees (i.e. technical and project steering committees), industry and public/civil society (e.g. NPOs etc.). Some of these human resources, skills and competencies highlighted include:

i. Development of baseline assessment by consultants/specialists in order to assess and evaluate the current air quality status of a study area;
ii. AQO duties amongst others include the coordination of matters of air quality within his/her jurisdiction; Ensuring representation in meetings with other government officials, industry, NGOs, and other stakeholders; Providing input and making decisions on behalf of his/her department on air quality matters at various air quality fora; Work with Environmental Management Inspectors on AQA matters; Input into the national atmospheric emissions inventory, Reporting on the state of air; Reporting on the implementation of AQMP for the jurisdiction; etc);
iii. Public/civil society – broad public participation in the AQMP process is an important step that will lead to greater "buy-in" and promotes the public's involvement in the development of the AQMP;
iv. Technical committee / advisory forum / Priority Multi-Stakeholder Reference Group (MSRG) – It should comprise of competent internal and external government officials whose departments have air quality-related functions or concerns and could include expertise from the private sector. The committee should be able to contribute meaningfully to the development and implementation of the AQMP.

Data and Information: the baseline assessment for AQMP as stipulated in the Manual, should be based on all available data and information including but not limited to: air quality data, air pollution sources, area description, and geography (defining the boundaries), description of the meteorology and climate of the area, population statistics, evaluation of air quality information based on available data (description of the existing air quality monitoring programme; evaluation of the QA/QC; evaluation of the current air quality. Other issues that the data must provide include sources and emission inventories, pollutants of concern, possible impacts and impact areas, priority air quality issues.

Time: Section 3.4.1 of the Manual (Task 1 and 2: Intervention Strategies and Action Plan) requires the AQMP to propose generic achievable timeframes for achieving the set intervention strategies ranging from short-term (1-2 years), medium-term (3-5 years) and long-term (5-10 years). In addition, the Manual requires that the AQMP once developed needs to be revised every 5 years.

Financial/Budget Capacity: This is the description of the budgetary needs to see through the entire AQMP development and implementation process. According to section 4.1.2 of the Manual, the AQMP must include an estimation of the expected costs and benefits of the intervention strategies.

The infrastructure: this is required for the development and implementation of AQMP as stipulated by the Manual includes the South African Air Quality Information System (SAAQIS) database in which relevant monitoring information can be obtained (i.e., location of monitoring stations, monitoring data, emission inventory, atmospheric dispersion modelling, and site access).

Activity component

Critical assumptions relating to the Activity component identified are:

- **Assumption 4:** Stakeholders are established and are actively involved in the assessment or AQMP process.
- **Assumption 5:** A thorough baseline air quality assessment is done using current and relevant information and is sufficient to inform the gap and problem analysis.
- **Assumption 6:** Gap and problem analysis is done.
- **Assumption 7:** The intervention strategies and action plans are technically and economically feasible and are indeed implemented.
- **Assumption 8:** The intervention strategies are sufficient to achieve ambient air quality standards.
- **Assumption 9:** The implementation plan is feasible (practical, timeframes, verifiable).
- **Assumption 10:** Monitoring, reporting and evaluation of the AQMP are done.

The activity component is the third component of the ToC map and in terms of the results-based pyramid, the key question asked for this component is “What are the steps required to develop and implement the AQMP?”. There are generally six steps that should be followed to develop and implement an AQMP as shown in Figure 3 (DEA, 2012; Sivertsen, and Bartonova, 2012). These steps are: (1) Establishment of stakeholder groups, defining the boundaries of the AQMP geographic area and the establishment of a baseline; (2) Gap and problem analysis; (3) Establish air quality goals; (4) Develop interventions and a plan to achieve air quality objectives; (5) Implementation of the intervention strategies; and (6) Monitoring, reporting and evaluation as outlined in the national framework for air quality management planning (DEA, 2012, 2018):

- (1) Establishment of stakeholder groups, defining the boundaries of the AQMP geographic area and the establishment of a baseline assessment report. This activity entails establishing the different committee groups as well as the establishment and issuing the draft air quality baseline report.
- (2) Gap and problem analysis: Stakeholders and the technical committees are consulted to evaluate the degree to which the baseline assessment is complete and allows for a clear understanding of air quality and impacts. Once the gaps are identified, the committee should initiate a problem analysis to determine the problems, associated causes of the problems and the effects. The gap and problem analysis should be documented as part of the AQMP, building on the baseline assessment section.
- (3) Establishing air quality goals: Based on the draft report and problem analysis, the project steering committee (PSC) and technical committee / advisory forum must meet and ratify a vision, mission as well as air quality management goals for the AQMP. Then a meeting should be scheduled through an invitation with the broader air quality stakeholder group. Thereafter a draft AQMP document as well as a decision on goals being met is made available to stakeholders.
- (4) Development of interventions and a plan to achieve air quality objectives: Intervention strategies for each of the problems identified is formulated by the PSC and technical committee / advisory forum. Once these intervention strategies have been identified, an action plan noting the implementation schedule should be tabled with the buy-in from stakeholders. Once agreed upon, the implementation plan is documented as part of the AQMP and submitted to relevant stakeholders for comments.
- (5) Implementation of the intervention strategies: After this stakeholder consultation and once comments have been incorporated and the document is finalised, an internal evaluation/review of the AQMP should be undertaken by the PSC. Once finalised, the AQMP is included in the IDP/ EMP/EIP. Implementation of the AQMP is implemented in a systematic manner based on the rules developed in the implementation strategy.
- (6) Monitoring, reporting and evaluation: It is important to monitor and evaluate the effectiveness of the emission reduction strategies on each of the priority pollutants to determine whether the goals are being achieved and the benefits realised. Appropriate indicators must be developed to monitor progress towards achieving compliance or other goals set. The annual report must be submitted by Provincial or Local authorities in terms of section 17 of the Air Quality Act, 2004 and section 16(l) (b) of the National Environmental Management Act.

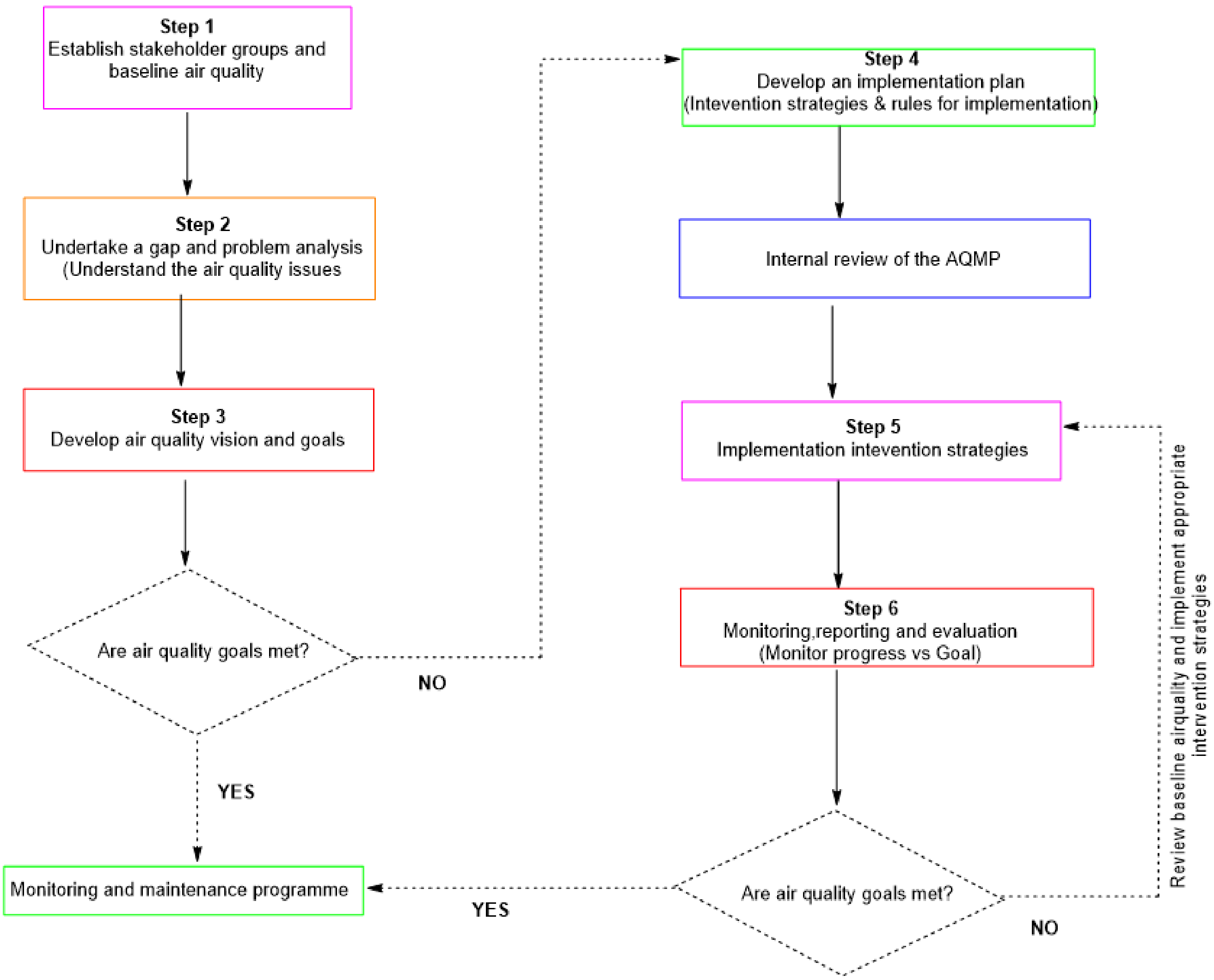

Figure 3: *AQMP development and implementation process (source: DEA, 2012)*

Output component

Critical assumptions identified relating to the output component are:

- **Assumption 11:** The AQMP report will address the gaps and problems identified, ensure successful implementation of intervention strategies, and ultimately ensure improvement of AQ in the airshed.

The output component in air quality management planning provides tangible results usually in reports and documents and the key question asked here is "What outputs do AQMPs produce?". The type of reports differs depending on the nature in which each plan was developed and documented. The following are some of the documents that are developed:

- Information material for stakeholder involvement (Background Information Document, relevant announcement, advertisements, media releases, etc.) - this document may be useful for public dissemination and posting on a web page.
- A comprehensive stakeholder database, comments, and response document (public participation document) could be helpful in effectively managing the public participation and communication process.
- Draft baseline assessment - this report covers amongst other the geography of the area (geographical boundaries, population, climate and other geographic information) and a description of the meteorology and climate; collecting and evaluating existing air quality information; Identifying sources and listing pollutants of concern; development of air quality management system (emissions inventory and dispersion modelling, and monitoring); and evaluation of current management and tools available.
- Gap and problem analysis document - the gap and problem analysis should be documented as part of the AQMP, building on the baseline assessment section.
- Draft AQMP - this document comprising the baseline assessment, gap and problem analysis, goals and implementation plan should be submitted as the draft AQMP.
- Final AQMP - after the stakeholder consultation and once comments have been incorporated and the document is finalised, the PSC should undertake an internal evaluation/ review of the draft AQMP to become the final AQMP.

Output components

Critical assumptions identified relating to the outcome component are:

- **Assumption 12:** The AQMP is gazetted or included in the IDP/EMP/EIP and influences decision-making.
- **Assumption 13:** The goal of an AQMP is to bring ambient air into compliance with the ambient air quality standards.
- **Assumption 14:** AQMP gives effect to chapter 3, section 16(1) of NEM:AQA requirements (intermediate outcome).

The outcome component in AQM planning is divided into immediate and intermediate outcomes. The immediate outcome depends on the sphere/level at which the AQMP is done. In declared priority areas, the AQMP must be approved and gazetted by the relevant minister/MEC. AQMPs for municipalities must be included in the IDP and for other government departments it must be included in EMPs and or EIPs. The question asked in this component is "what immediate and intermediate outcomes does the AQMP deliver?".

According to Euripidou et al., (2022), the objective of NEM:AQA read in line with NEMA is to develop means to avoid air pollution and enhance air quality which then ultimately gives effect to several constitutional rights. To achieve this objective, one of the key regulatory instruments mandated by the act is the NAAQS which set out ambient pollutant limits for eight pollutants, including NO_2, SO_2, PM_{10} and $PM_{2.5}$ (DEA, 2009, DEA, 2012; Euripidou et al., 2022). The objective of the AQMP as one of the instruments is therefore to give effect to NEM:QA and the constitution. The medium to long-term objectives stipulated in the act are therefore to:

a. To protect the environment by providing reasonable measures for–
i. the protection and enhancement of the quality of air in the Republic;
ii. the prevention of air pollution and ecological degradation; and
iii. securing ecologically sustainable development while promoting justifiable economic and social development; and
b. To give effect to section 24(b) of the Constitution in order to enhance the quality of ambient air for the sake of securing an environment that is not harmful to the health and well-being of people.

Impact component

The critical assumption identified relating to the impact component is:

- **Assumption 15: AQMP enables a progressive realization of the environmental right contained in section 24 of the constitution.**

The question asked in this component is "what impact does AQMP aim to achieve?" and that is the realisation of core human rights contained in section 24 of the Constitution (1996), which states that:

"Everyone has the right —
a. to an environment that is not harmful to their health or well-being; and
b. to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that —
i. prevent pollution and ecological degradation;
ii. secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development."

Discussion

In evaluation studies, assumptions can either be valid or invalid and can either be a resource or risk to the success of a programme, therefore, it is essential to determine assumptions underpinning an intervention or programme such as the AQMP (van Es et al., 2015; Archibald et al., 2016). If these assumptions are flawed or unfounded, the intervention/programme will probably not work as planned and it is thus important to do a risk analysis to determine which assumptions are most critical to monitor (van Es et al., 2015). Critical assumptions are therefore a good basis for risk management in that monitoring these assumptions allows for a timely response to new information, planning, and strategizing as well as deciding on the best strategic reactive steps to take in complex contexts/processes (van Es et al., 2015).

As a first step towards evaluating the effectiveness of AQMPs in South Africa, the aim of this study was through the application of the ToC approach, to identify critical assumptions and underpinning AQMP development and implementation in South Africa. This study is limited only to the identification of the assumptions and did not evaluate or test the validity of these assumptions. Further to this, this study conducted a literature review to identify risks associated with these critical assumptions as shown In Table 2. The study resulted in the identification of 15 underlying critical assumptions within different components of the ToC map (i.e. design, input, activities, output, outcome, and impact components, see Figure 2). These assumptions are considered to be critical ones although this study acknowledges that they are not the only ones underpinning AQMP development and implementation in South Africa. However, the ones identified in this study are found to be the fundamentally important ones that may have a significant impact on the success of developing and implementing AQMPs as a policy instrument in South Africa.

Table 2 shows the 15 assumptions identified and their associated risks toward the successful development and implementation of AQMP in South Africa. In addition, the table also provides a link between the identified assumptions and risks from existing local and international literature in the air quality sector. The literature review references, therefore, supplement the argument in this study that these assumptions and risks identified are indeed critical and could be having a significant impact on AQMP development and implementation. It is important to highlight

Table 2: *Critical assumptions, key risks and implications on the effectiveness of air quality management planning as well as the relevant existing literature.*

Component	Nr.	Critical assumption	Key risk	Relevant local & international literature informing the key risk
System Design	1	**Legislation driven:** The legislative framework provides guidance towards AQMP development and its implementation	Not all spheres of government have been able to develop and implement AQMPs. There is insufficient guidance on the development and implementation of AQMP	DFFE, 2021a; Gollata, and Newig, 2017; Scorgie, 2012; Tshehla, and Wright, 2019.
System Input	2	**Resources available:** Resources are available to develop and implement the AQMP	There are insufficient resources such as skills and competencies, infrastructure, data and information, and budget in place to implement the AQMP	DFFE, 2021a; DFFE, 2021b Engelbrecht, and van der Walt, 2007; Engelbrecht, and van der Walt, 2007; Gulia et al., 2015; Moreoane et al., 2021; Naiker, 2007; Naiker et al. 2012; Scorgie, 2012; Sivertsen, and Bartonova, 2012); Tshehla, and Wright, 2019; Roomaney et al., 2022.Molman et al., 2022; Alberts et al., 2022
	3	**Cooperation exists:** Cooperative governance exists between government stakeholders	Poor communication and coordination within municipalities and departments resulting in poor implementation of the AQMPs.	Engelbrecht, and Van der Walt, 2007; Naiker et al., 2012; Naiker 2007; Scorgie, 2012, Moolman et al., 2022, Maissner et al., 2016, Bourblanc, and Blanchon, 2014, Colvin et al., 2008, Bourblanc, 2012.
System Activity	4	**Engaged stakeholders:** Stakeholders are established and are actively involved in the assessment or AQMP process	The public and other stakeholders are unwilling to participate or do not participate in good faith which can lead to uninformed decision-making processes and undermines the subsidiarity principles. Concerns over the credibility of the process	DEA 2018 Engelbrecht, and van der Walt, 2007; Gulia et al., 2015; Scorgie, 2012; Sivertsen, and Bartonova, 2012; Berke, and Godschalk, 2009; Lyles, and Stevens, 2014.
	5	**Effective baseline:** A thorough baseline air quality assessment uses current and relevant information to inform the gap and problem analysis	Poor quality reports could lead to misleading information relating to AQM planning	Moreoane et al., 2021, Roomaney et al., 2022
	6	**Existing gap analysis:** Gap and problem analysis are done	Incomplete baseline assessment, lack of understanding of air quality and impacts as well as no determination of the problems, associated cause of the problems and the effects.	Moreoane et al., 2021; DEA 2012
	7	**Implementable strategies:** The intervention strategies and action plans are technically and economically feasible and implemented	Poor intervention strategies and implementation plans that are not implementable thus no improvement in ambient air quality	DEAT 2009; Moreoane et al., 2021
	8	**Sufficient interventions:** The intervention strategies are sufficient to achieve ambient air quality standards		
	9	**Feasible achievement:** The implementation plan is feasible (practical, timeframes, verifiable)		
	10	**Monitoring in place:** Monitoring, Reporting and Evaluation of the AQMP is done	Poor or no understanding of the AQMP performance on: (1) extent to which the AQMP was implemented; (2) air quality management initiatives; (3) compliance of the AQMP to the applicable standards; (4) fourthly, how the area performed in achieving the targets; and lastly, any amendments to the plan.	Moreoane et al., 2021; DEA, 2012, Gulia et al., 2020; Roomaney et al., 2022.
System Output	11	**Report matches objectives:** AQMP report addresses the gaps and problems identified, ensures successful implementation of interventions strategies and ultimately ensures improvement of AQ in the airshed	The AQMP report quality does not address the gaps and problems identified and does not ensure successful implementation of interventions strategies and ultimately ensure improvement of AQ in the airshed	DEA, 2018; Engelbrecht, and van der Walt, 2007; Gulia et al., 2015; Scorgie, 2012; Sivertsen, and Bartonova, 2012; Moreoane et al., 2021
System Outcome	12	**AQMP is enforceable and included in wider plans:** The AQMP is gazetted or included in the IDP/EMP/EIP and influences decision making	Exclusion of the AQMP in the IDP/EMP/EIP leads to uninformed decisions or total exclusion on air quality matters in strategic planning.	Engelbrecht, and VD Walt, 2007.
	13	**Air quality standards met through AQMP:** The goal of an AQMP is to bring ambient air into compliance with the ambient air quality standards	The AQMP does not bring the ambient air into compliance with the ambient air quality standards	Lack of literature in the air quality sector
	14	**AQMP meets legislation requirements:** The AQMP gives effect chapter 3, section 16(1) of NEM: AQA requirements	The AQMP as a policy instrument does not help realise the indented objectives of the NEM: AQA	Alberts et al., 2021a; Alberts et al. (2021b) about EIA. Moolman et al., 2022 (water use applications) Lack of literature in the air quality sector
System Impacts	15	**Realisation of the environmental right:** AQMP enables a progressive realisation of the environmental right contained in Section 24 of the constitution	AQMP implementation does not lead to a progressive realisation of the environmental right contained in Section 24 of the constitution	Alberts et al., 2021; Alberts et al. 2022; Moolman et al., 2022. Lack of literature in the air quality sector

that there was no literature found specifically talking to some of the identified assumptions and risks such as assumption 8 and therefore more research is required in these areas.

In assumption 1, it is assumed that the current legislative framework in South Africa as described in the design component of the ToC provides sufficient guidance toward AQMP development and implementation. However, literature shows that not all spheres of government have developed and implemented their AQMPs since the promulgation of NEM:AQA in 2004. Two provinces, 34 district municipalities and many more local municipalities still have no AQMPs in place (DFFE, 2021a and 2021b; Tshehla, and Wright, 2019). There is, therefore, a need for further research relating to the evaluation or testing of this specific assumption.

Literature review shows that assumption 2 which states that resources are available to develop and implement the AQMP, is already proving to be flawed in practice in that many municipalities in South Africa and elsewhere still cannot effectively implement AQMPs due to the lack of budget, skills and competencies, stakeholder commitment, weak policies, standards and regulations, as well as the absence of air quality data and emission inventories (DFFE, 2021a; DFFE, 2021b, Engelbrecht, and Van der Walt, 2007; Gulia et al., 2015; Moreoane et al., 2021; Naiker et al., 2012; Scorgie, 2012; Sivertsen, and Bartonova, 2012; Tshehla, and Wright, 2019). It is also clear from existing literature that there is currently a skills and competency gap especially in government towards to AQMP system in South Africa (DEA, 2018; Engelbrecht and van der Walt, 2007; Engelbrecht, and van der Walt, 2012; Naiker, 2007; Naiker et al., 2012). In addition, for an AQMP to be effectively and efficiently developed and implemented, the gap in technical capacity and skills such as engineering control, air quality modelling, identification of sources and emission quantification as well as air pollution risk assessment more so in local municipalities is a matter that requires urgent prioritisation (Naiker et al., 2012; Engelbrecht, and van der Walt, 2007; Engelbrecht, and van der Walt, 2012).

Moreover, according to an international research-based practical guide to the principles and steps to developing AQMP, the AQMP development and implementation process should include inputs from various role players including industry, groups and individuals (Sivertsen, and Bartonova, 2012). Naiker et al., (2012), also contend that partnerships and cooperative governance are important contributors to South Africa's current governance setup and should be encouraged to drive air quality management interventions. This study, therefore, suggests that the assumptions that cooperative governance exists between government (assumption 3) and that other stakeholders (such as the public) are established and are actively involved (assumption 4) are important to monitor and may also require further evaluation. An earlier study, however, found that air quality management in South Africa generally faces challenges such as a lack of political will, consultation, and communication as well as non-utilisation of existing planning tools (Naiker et al., 2012). A similar situation is also found in the water governance sector where it is found challenging to establish effective intergovernmental relations and co-operative governance in South Africa (Moolman et al., 2022; Meissner et al., 2016; Bourblanc, and Blanchon, 2014; Colvin et al., 2008; Bourblanc 2012). Considering at the manner in which South Africa's air quality governance is structured with the delegation of key functions to local government, there is therefore a need for further research to be conducted to explore the validity of these assumptions at a bigger scale pertaining to the AQMP policy instrument in South Africa. This will give a clear picture of the situation within the different spheres of government in South Africa.

As an output of the ToC component, good quality baseline assessment and AQMP reports should have clear objectives, factual and truthful information, policies, public participation as well as be clear in the implementation and monitoring interventions (Berke, and Godschalk, 2009; Lyles, and Stevens, 2014). This then suggests the importance to evaluate and monitor the assumptions (5, 6, and 11) that in the current AQMP system, thorough baseline air quality assessments are done using reliable, current, and relevant information to inform the gap and problem analysis. This could lead to a risk that intervention strategies and implementation plans in those AQMPs could be based on inaccurate and misleading information which then makes them unrealistic to implement. This study suggests that similar to the EIA reports, quality becomes an important component to effectiveness since the extent to which the plan achieves its objectives is based on adherence to its procedural requirements and substantive purpose (Sadler, 2012; Sandham et al., 2013). However, it has been found in South Africa's water use licence application (WULA) system that poor quality reports based on weak impact assessments have played a role towards an ineffective system in South Africa (Moolman et al., 2022). This study argues that evaluating the completeness and substance quality of AQMP reports can help in providing clarity on whether these plans operational mechanisms are realistic or not towards meeting their own objectives.

Assumptions 7 and 9 assume that the intervention strategies and action plans are technically and economically feasible and implemented. The risk associated with this is that poor intervention strategies and implementation plans may not be implementable thus no improvement in ambient air quality. A similar study that evaluated the quality of the first and second Vaal Triangle Airshed Priority Area Air Quality Management Plans has found that there are some gaps in the intervention strategies despite the reports being found to be satisfactory overall (Moreoane et al., 2021).

Furthermore, it is assumed that effective monitoring, reporting and evaluation is done in the AQMP development and implementation process (assumption 10). The risk associated with this is a poor or no understanding of the AQMP performance on (1) the extent to which the AQMP is implemented; (2) air quality management initiatives; (3) compliance of the AQMP to the applicable standards; and (4), how the area performed in achieving the targets. A recent study by Roomaney et al., (2022), however, suggests that reducing the levels of air pollution emissions is directly proportional to the reduction of non-communicable and infectious diseases and there is a need to increase efforts to have a comprehensive system of monitoring stations measuring ambient air quality to gather accurate and reliable information in South Africa.

Moreover, once the AQMP has been developed it needs to be gazetted if it is at the priority area level, or included in the EIP and/or EMP if it is a provincial level, and included in the IDP if it is at the municipal level as required by NEM: AQA and the Municipal Systems Act as per assumption 12 (DEA, 2018). Engelbrecht, and van der Walt, (2007), however, earlier found that only a few municipalities had included their AQMPs in their IDPs and 16 years later it remains unclear the extent to which the existing AQMPs have been incorporated in their IDPs. Again, further research is required to address this assumption.

In the end, the goal of AQMPs as a policy instrument in South Africa is to give effect to chapter 2 of NEM: AQA which ultimately seeks to realise the human environmental right stipulated in section 24 of the constitution (assumptions 13, 14 and 15). Such objectives and targets aim to reduce air pollution by identifying and mitigating anthropogenic activities that cause negative impacts on human health and the environment through compliance with the NAAQS. The risk associated with these assumptions is the ineffectiveness of the AQMP as a policy instrument in achieving its mandated objectives to bring the ambient air into compliance with the ambient air quality standards, to help realise the intended objectives of the NEM: AQA as well as lead to a progressive realisation of the environmental right prescribed in section 24 of the constitution. A similar study has found the protected areas system policy instrument to be effective in contributing positively to an environment that is not harmful to our health and well-being, as well as realising the rights encapsulated in Section 24(b) in South Africa and this remains to be tested for AQMPs in South Africa (Alberts et al., 2022).

Conclusion

In conclusion, this study adopted the ToC approach to identify 15 critical assumptions underlying the AQMP development and implementation system in South Africa. A further literature review was conducted to identify the risks associated with these critical assumptions. This study was only limited to identification and did not evaluate each of the assumptions and risks. This can be regarded as a first step towards a better understanding of the effectiveness of air quality management plans in South Africa. Although not the only assumptions, those that have been identified through the Theory of Change approach are considered to be fundamental to the development and implementation of AQMPS as a policy instrument in South Africa.

The findings in this paper suggest that the current AQMP development and implementation process could be fundamentally based on flawed assumptions which may be the underlying factors for current challenges in municipalities being unable to develop and implement their AQMP since the promulgation of the NEM:AQA in 2004. In addition, evidence is found in the literature proving that some of these assumptions are indeed flawed and already manifesting in practice and are therefore a risk to the effectiveness of the current air quality management planning system as a policy instrument. It is however suggested that to get a clearer view of these challenges, future research should be conducted to test the validity of all these assumptions in order to fully provide a fundamental understanding of how AQMP process works in South Africa and elsewhere. This will also provide solutions for avoiding or mitigating risks associated with these assumptions. Some of the assumptions and risks identified in this study such as resource availability, public participation and cooperative governance have also been identified in other environmental governance systems. With the ongoing increase in air pollution challenges globally and locally, the assumptions and risks associated with new and existing air quality policy instruments such as the AQMP must be effectively managed for these policies to effectively achieve their intended objectives which are ultimately aimed toward realising an environment that is not harmful to the health and well-being of humans.

Note

An earlier version of this paper was presented at the National Association of Clean Air (NACA) Conference in October 2021 and was published in its Proceedings.

Theory of Change approach limitations

A limitation of the ToC approach is that the method is based on the causal-effect assumption. Meaning that the method assumes that if one of the components is correctly executed then the following step or component will also happen.

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Appendix

Appendix 1: *Workshops conducted with various stakeholders during June 2021 and October 2022*

Workshops	Workshop type and purpose	Stakeholders	Organisation
Step 1	South African Specialist Workshop	5x NWU academic staff members	North-West University
Step 2.1	Academia workshops	2x Senior Lecturers	1x University of Cape Town; 1x University of Johannesburg
Step 2.2	Specialist// consultant workshops	5x Senior Consultants	3x Airshed Planning Professionals (Pty) Ltd; 1x Davhana Geotech Solutions (Pty) Ltd); 1x Xilalelo Project Managers
Step 2.3	Industry workshops	5 x industry environmental practitioners/officers	Eskom Holdings SOC Ltd; Anglo American Platinum
Step 3	Regulator workshops	11x government officials	DFFE; GDARD; City of Johannesburg; Gauteng provincial government; Knysna Local municipality; LEDET;
Step 4	NPO discussions	(Vaal Environmental Justice Group (VEJA) members and Vukani Environmental Justice Movement in Action	VEJA and Vukani Environmental Justice Movement in Action
Step 5	International specialist inputs: Broader perspective on the history of air quality legislation in South Africa and global point of view.	Ex-government official now based abroad	None
Step 6	NACA conference presentation: 06 October 2021	Over 100 participants	Academia, government officials, industry, etc.
Step 7	UK perspectives on the assumption and effectiveness of air quality policy instruments like air quality action plan with specific reference to UK's air quality action plans	An official in the Environmental Health – Newcastle-under-Lyme Borough Council.	Newcastle-under-Lyme Borough Council.

Research article

Environmental controls on air pollution dispersion over Richards Bay, South Africa

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Abstract
Air pollution dispersion over Richards Bay, South Africa is studied using satellite, reanalysis and in-situ measurements. Near-surface concentrations of trace gases and particulates reach high concentrations under dry stable 'berg' winds. Temporal records of CO, NO_2, O_3, $PM_{2.5}$, SO_2 (2000-2023) exhibit no trend and short-term dose excedances of individual pollutants are rare and confined to winter mornings. Regional point-to-field correlation maps of a Richards Bay winter air pollution index found that anomalous warming of the west Indian Ocean accelerates the jet stream over Madagascar and pulls smoke- and dust-laden north-westerly winds across the South African plateau, implicating long-range transport. At daily and hourly time scales dewpoint temperature and boundary layer height best indicate changes in local air pollution dispersion that impact respiratory health. A case study of 15-17 June 2021 revealed a 10°C thermal inversion caused by negative sensible heat fluxes of -40 W/m^2 through the night, leading to SO_2 concentrations above 100 ppb in the morning along the main access road (28.8°S, 32°E). Poor dispersion seldom happens in the summer when turbulent mixing and rainfall cleanse the air.

Keywords
Richards Bay, South Africa, meteorology, air pollution dispersion

Introduction

Urban, industrial and agricultural activities generate wealth but often incur atmospheric emissions that can degrade ecosystems and impair respiratory health (Akimoto 2003, World Bank 2016, WHO 2021). Manufacturing and power generation in the South African Highveld emit ~10^4 Tons km^{-2}/yr of carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2) and fine particulates ($PM_{2.5}$), which lead to acidic deposition (Josipovic et al. 2011, Conradie et al. 2016, Jury 2017, Tularam et al. 2021). Local pollutants are joined by regional smoke plumes from tropical deforestation and Kalahari dust plumes (Piketh et al 1999, Silva et al. 2003, Battachan et al. 2012, Ma et al. 2013). As emissions disperse under sunlight, photochemical reactions generate O_3 and reduced visibility. In contrast with the interior plateau, KwaZulu-Natal has a humid climate underpinned by an anticyclonic circulation pulsed by eastward moving troughs (Preston-Whyte & Tyson 1988, Jury & Freiman 2002). Although marine winds of ~ 7 m/s tend to disperse 10^5 Tons/year of pollutants along the coast near Durban (Scorgie 2012, Gopaul et al. 2019), unhealthy concentrations prevail about 5% of the time in the dry winter season when emissions are trapped beneath a thermal inversion (Simpson & McGee 1996, Diab & Matooane 2003, Ramsay 2010, Jury & Buthelezi 2022).

South Africa's northeast coast is an increasingly popular destination due to its year-round warm weather. A new road network connecting Maputo and Durban has increased trade and tourism in the Zululand area, leaving small areas of wealth surrounded by rural poverty. Richards Bay (28.8°S, 32°E) has evolved from a fishing village to a coastal resort in the 1950s (Aniruth 1997, Cubbin 1998). In the 1970s a 60 km^2 deep-water port was constructed for the export of minerals and industrial products amounting to ~100 million Tons/year. Richards Bay's maritime trade and supporting industries employ more than 10,000 people making up ~ 50% of formal jobs, whose revenue contributes to a municipal budget of ~ R1400 million/year. On-going efforts to diversify the economy toward tourism have included a waterfront marina and beaches, and lakefront golf course and rustic lodges. Environmental use of natural amenities is at odds with the city's role as an industrial hub (Magi and Nzama, 2002). The area is susceptible to pollution from land- and water-borne pathways that seep into recreational and residential areas. Atmospheric emissions of ~7000 Tons/day of CO_2 and ~100 Tons/day of CO, $PM_{2.5}$, O_3, SO_2, NO_2, hydrogen fluoride and ammonia tend to accumulate during the dry winter season (May-Aug) under weak westerly winds (Jury 2000, Petzer et al. 2008). One-quarter of the 100,000 downtown residents make clinical visits every year for allergic and asthmatic reactions (Jaggernath 2013, Okello et al. 2020). Airborne pollutants are monitored by the Richards Bay Clean Air Association and reported to the South Africa Air Quality Information System (SAAQIS). Although dose exceedances are rare for SO_2 and particulates (Okello et al. 2018), sinus allergies are common and environmental stress continues amidst an industrial agenda. Historical development plans that put major industries one kilometer from the commercial centre (Figure 1a-c) can't be undone, so the city maintains narrow buffer zones between industry and urban areas.

Richards Bay has a southeast facing coast swept by warm currents and stormy seas. The sub-tropical weather is changeable and humid winds create wetlands dotted by lakes. Microplastics are dense (>2%) near the waterfront and harbour effluents infiltrate the seafloor sediment (Mehlhorn et al. 2021). The port is bound by jetties that prevent the northward flux of sand (Mitchell et al. 2005), so beaches are retreating and limit development options.

Point source emissions form narrow plumes that disperse over space and time. Short-term exposure has marginal impact, but long-term dose maps can be used to link atmospheric dispersion to respiratory health risk. In that regard, satellite measurements of near-surface air pollutants (Burrows et al. 2011, Korhonen et al. 2014, Sundström et al. 2015, Krotkov et al. 2016) can be assimilated with in-situ observations and emission inventories by sophisticated air chemistry models to enable the study of trace gases and particulates over urban areas. Here, the following questions are addressed: i) what is the extent of local air pollution from hourly to annual time scales? ii) how do the winter climate and local weather influence air pollution concentrations? iii) are distant pollution sources involved in local episodes, iv) what mitigating actions can be taken to reduce health risks?

Data and Methods

MERRA2 air chemistry data assimilation (Molod et al. 2015, GEOS-5 2016, Gelaro et al. 2017, Randles et al. 2017) provides monthly surface CO, O_3, $PM_{2.5}$ and SO_2 concentrations at ~ 50 km resolution from Jan 2000 – Nov 2023. An air pollution index was formed by summing the four values (ppb) at the grid point 28.8°S, 32°E. Daily air constituents NO_2 and SO_2 derive from OMI satellite (Lamsal et al. 2014) and $PM_{2.5}$ from MERRA2

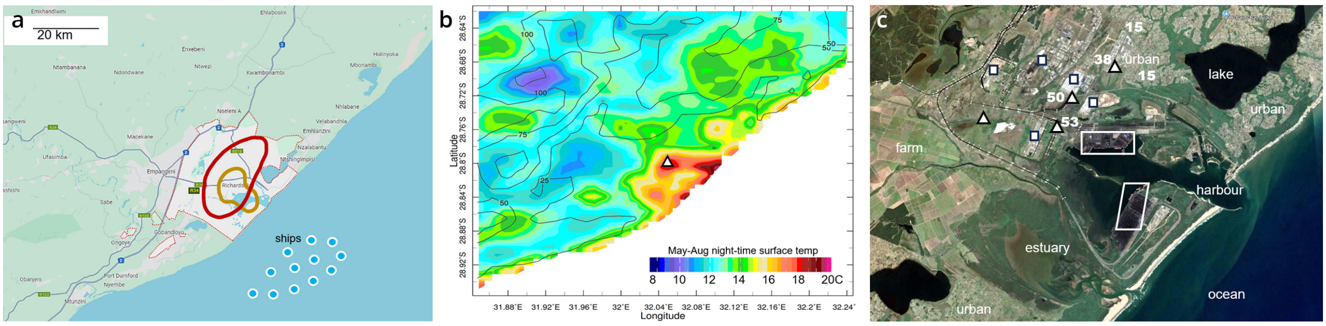

Figure 1: *a) Map of Richards Bay area and main roads, with dots representing awaiting ships (in Jan 2024), and red / orange outlining high SO_2 / PM_{10} concentration (adapted from Petzer et al. 2008). b) winter mean nocturnal land surface temperature at 1 km resolution from infra-red satellite with elevation contours. c) Close-up satellite photo of the harbour with weather and air pollution stations Δ, point-source emissions □, coal loading zones outlined white, numbers refer to average of daily maximum SO_2 (Petzer et al. 2008).*

Table 1: *Datasets used in the analysis*

Acronym	Name	Space, time resolution	Quantity
CALIPSO	Cloud-Aerosol Lidar & Infrared Pathfinder Satellite Observation	1 km on N-S slice, weekly	Particulate density
ERA5	European Community reanalysis version 5	25 km, daily, monthly	Near-surface meteorology
HYCOM	Hybrid coordinate ocean model reanalysis v3	10 km daily	Sea surface temperature, ocean current
HYSPLIT	Hybrid Lagrangian Trajectory model	25 km	Long-range transport via near-surface airflow
MERRA2	Modern era reanalysis for research & applications with GEOS-5 air chemistry	50 km, daily, monthly	Near-surface CO, O_3, $PM_{2.5}$, SO_2
MODIS	Infrared and visible band radiometer	1 km	Surface temperature, vegetation, fires
OMI	Ozone Monitoring Instrument	25 km, twice daily	Near-surface NO_2 & SO_2 concentration
SAAQIS	South African air quality information system, RBCAA monitoring	Station, hourly	Surface $PM_{2.5}$, PM_{10}, SO_2 conc, meteorology
SAWS	South African Weather Service	Radiosonde, surface obs.	Air & dew temp, wind velocity, air pressure

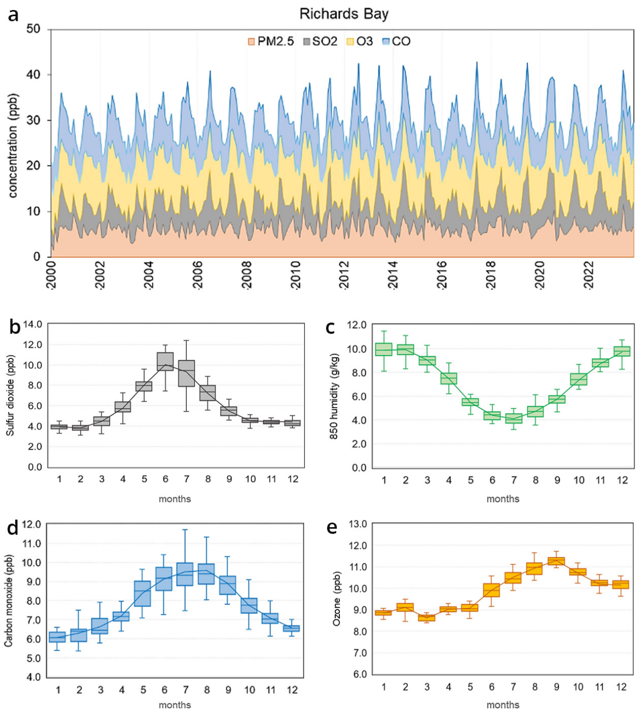

Figure 2: *a) Temporal record of monthly MERRA2 assimilated air pollution constituents in Richards Bay, plotted in aggregate. Box-whisker mean annual cycle of monthly: b)* SO_2*, c) 850 hPa specific humidity, d) CO, and e)* O_3*.*

at 28.8°S, 32°E in the period Oct 2004 – Nov 2023. Gaps in polar-orbiting satellite coverage were reduced by application of a 3-day running maximum. Hourly $PM_{2.5}$, PM_{10}, SO_2 and meteorology measurements in Richards Bay derive from in-situ stations (Fig 1c) reported to SAAQIS. MODIS satellite infrared and visible band radiance was analyzed for night-time thermal patterns, vegetation fraction and fire locations at 1 km resolution.

The monthly, daily and hourly near-surface meteorological data at 28.8°S, 32°E were derived from the 25 km resolution European Reanalysis v5 (ERA5, Hersbach et al. 2020) and include: air and dewpoint temperature, wind velocity, specific humidity, sensible heat flux and boundary layer height (BLH) or mixing depth. Surface values are preferred given the low elevation of Richards Bay (Fig 1b), but to quantify transport and dispersion the 925 hPa (~700 m) winds and 850 – 1000 hPa (1500 – 10 m) temperature difference 'delta T' were calculated. Hourly analysis of air pollution events utilize in-situ weather station data: air and dewpoint temperature, air pressure and solar radiation, wind speed and direction. Table 1 summarizes the dataset characteristics. One limitation is the ~50 km resolution of MERRA2, which makes it too coarse to identify the dispersion footprint of Richards Bay, necessitating finer scale products and in-situ measurements.

The mean annual cycle of monthly CO, O_3, SO_2 and 850 hPa humidity was calculated to identify the winter months May-August as most important (Shikwambana & Sivakumar 2019). Statistical pearson-product cross-correlations were calculated between the satellite/model air constituents and independent ERA5 meteorology time series at Richards Bay. The various records cover 288 months (2000-2023), 7000 days (2004-2023), and 2950 hours (May-Aug 2021). Significance at 95% confidence was evaluated according to the degrees of freedom (deflated for persistence). The appropriate thresholds are $r \geq |0.41|$ monthly, $|0.17|$ daily, and $|0.21|$ hourly. Pulsing of the weather was revealed by application of wavelet spectral analysis to the daily time series of ERA5 dewpoint temperature. Dispersion footprints were mapped using OMI satellite NO_2 and MERRA $PM_{2.5}$ data during the winter. The daily satellite NO_2 and SO_2 concentration record at Richards Bay was used to identify the winter of 2021 for further study. Maps of satellite NO_2 and height sections of CO concentration were calculated and compared with wind observations from Durban airport. The mean diurnal cycle was calculated from hourly in-situ SO_2 and weather data, and surface airflow patterns were analyzed by vector averaging May-Aug 2021.

To understand the influence of inter-annual climate variability, the Richards Bay winter air pollution time series was correlated with regional fields of ERA5 sea level air pressure, 500 hPa geopotential height, sea surface temperature and NOAA satellite net outgoing longwave radiation (OLR) representing atmospheric moisture (May-Aug 2000-2023). Ranking the air pollution index time series, the top-20 winter months were identified and composite atmospheric circulation anomalies were calculated from 1000 to 100 hPa (0-12 km height).

From the Richards Bay SO_2 time series an air pollution event 15-17 June 2021 was identified for detailed study of local weather using in-situ observations. A radiosonde profile at Durban airport 02:00 16 June 2021 was analyzed for vertical structure of wind, air temperature and dewpoint 1000 – 700 hPa (0-3 km). It is located 150 km southwest of Richards Bay and may be considered representative of KwaZulu-Natal. Regional smoke plumes were analyzed from MERRA2 assimilation 15-17 June 2021, and satellite fire density (FIRMS 2023) and vegetation fraction were analyzed. Lastly, a particulate event was analyzed for 4-5 July 2022. Local measurements and a north-south height section of CALIPSO satellite particulates (Winkler et al. 2007) were analyzed. HYSPLIT back-trajectories were calculated (Stein et al. 2015) to identify long-range transport of dust and smoke plumes from distant sources and local hourly weather data were obtained on wind speed and direction, sensible heat flux and boundary layer height.

Results

Geography and climate

The coastal plains near Richards Bay align in a SW-NE axis and rise slowly inland to the hills of Zululand. The Mhlatuze River valley forms a basin around the harbour (Fig 1a-c). Average winter night-time surface temperatures decrease westward from 20° to 10°C just 40 km inland. Over the city, nocturnal temperatures remain elevated above 16°C, constituting the urban heat island. Figure 1a-c illustrates emission and station

Table 2: *Simultaneous cross-correlation of MERRA2 surface air constituents and ERA5 meteorology variables over Richards Bay: a) monthly 2000-2023, b) daily 2004-2023, c) hourly May-Aug 2021; bold values significant at 95% confidence. Meteorological parameters are surface except: 925 = 0.7 km, 850 = 1.5 km, 700 = 3 km elevation; abbreviations: air poll. = sum of all constituents, p.evap = potential evaporation, w.speed (wind), L.H.F. and S.H.F. = latent and sensible heat flux, U V W = east, south and vertical airflow, q = specific humidity, T dew (dewpoint), delta T = lapse rate (+ stable), B.L.H. = boundary layer height.*

monthly	air poll	$PM_{2.5}$	SO_2	O_3	CO
$PM_{2.5}$	0.63				
SO_2	0.88	0.36			
O_3	0.52	0.14	0.23		
CO	0.87	0.27	0.77	0.56	
rain	-0.53	-0.19	-0.52	-0.26	-0.55
pot.evap	-0.60	-0.13	-0.74	-0.14	-0.58
w.speed	-0.04	0.01	-0.32	0.53	0.01
L.H.F.	-0.55	-0.18	-0.49	-0.35	-0.63
S.H.F.	-0.55	-0.18	-0.65	-0.13	-0.50
U 850	0.67	0.42	0.48	0.60	0.60
V 850	-0.12	-0.10	0.06	-0.34	-0.17
W 700	-0.11	-0.09	-0.10	0.04	-0.11
q 850	-0.80	-0.18	-0.82	-0.48	-0.83
daily	**PM2.5**	**SO_2**	**NO_2**	**netOLR**	**T dew**
SO_2	0.08				
NO_2	0.10	0.63			
netOLR	-0.04	0.18	0.18		
T dew	-0.02	-0.32	-0.35	-0.26	
U 925	0.23	0.16	0.18	0.07	-0.28
V 925	0.14	-0.05	-0.05	-0.19	-0.14
delta T	0.17	0.18	0.19	0.30	-0.08
L.H.F.	-0.09	-0.15	-0.17	-0.09	-0.14
hourly	**$PM_{2.5}$**	**SO_2**	**S.H.F.**	**B.L.H.**	**U wind**
SO_2	0.00				
S.H.F.	0.06	-0.09			
B.L.H.	-0.08	-0.22	0.43		
U wind	0.13	-0.05	-0.22	0.07	
V wind	0.15	-0.31	0.11	0.44	0.70

locations, coal loading zones, and the high pollution footprint aligned to the coast.

Time series of monthly air constituents at Richards Bay over the period 2000-2023 are presented in Fig 2a, with mean annual cycles in Fig 2b-e. None of the variables contain significant trends (r^2 < 1%). Mean annual cycles are noteworthy and show peaks for SO_2 in June, for CO in July, and for O_3 in August-September. 850 hPa specific humidity at Richards Bay negatively correlates with air pollutants and shows a minimum in June-July. Table 2a summarizes the temporal cross-correlations with monthly

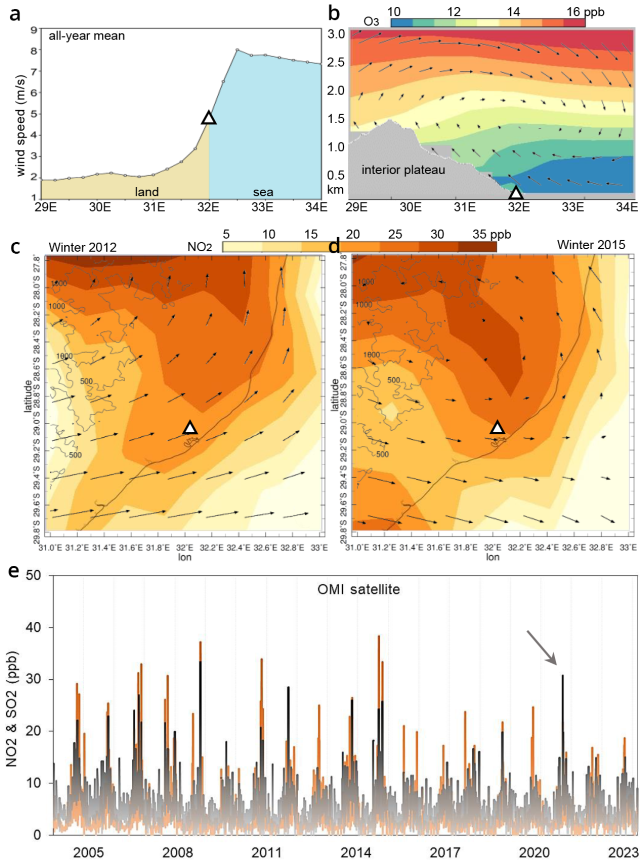

Figure 3: *West-east section on 28.8S of 2000-2023 mean: a) wind speed, b) height section of O_3 and zonal circulation (vector, max 3 m/s). Mean winter maps of OMI satellite NO_2: c) May-Aug 2012 and d) May-Aug 2015 with near-surface wind (vector, max 3 m/s). e) Temporal record of daily OMI satellite observed NO_2 (orange) and SO_2 (grey) in Richards Bay. Arrow points to case study 15-17 June 2021.*

weather conditions. $PM_{2.5}$ is quite insensitive except for U 850 wind (r = 0.42) indicating that westerlies enhance particulate dust in Richards Bay. SO_2 and CO are highly correlated (r = 0.77) and also increase under westerly winds and in dry weather (q 850 humidity, r = -0.82). Ozone behaves similarly to most air constituents except to increase with wind speed (r = 0.53) suggesting importation from distant sources. The apparent high correlation values in Table 2a derive mainly from seasonality.

Figure 3a illustrates differences in the land-sea climate along a section through Richards Bay. Surface winds over the sea exceed 7 m/s while long-term averages over the coastal plains are 2 m/s. Channelling of airflow by the South African escarpment helps maintain strong gradients in dispersion across the coast. As mentioned earlier, O_3 is a secondary trace gas formed by the oxidation of CO in the presence of NO_2 and sunlight (Ryu and Jenkins 2005, Zhang et al. 2010); it is reduced over the ocean by halogens (Read et al. 2008, Saiz-Lopez & Fernandez 2016). In Figure 3b the long-term average height section of O_3 shows an increase with height and distance from the coast. Clean marine air is swept inland by low-level easterly winds and summer-time sea breezes. The mean zonal circulation exhibits overturning, with rising motion over the Drakensberg, upper westerly winds and sinking motion over the Mozambique Channel.

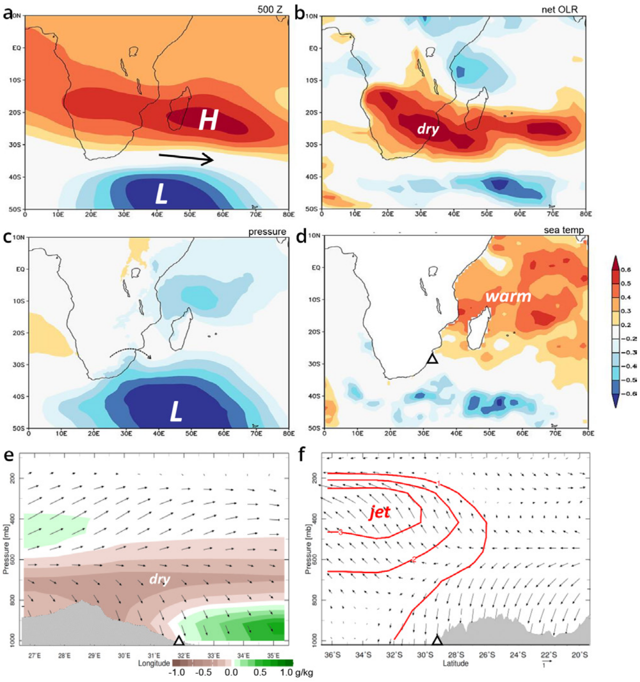

Figure 4: *Correlation of May-Aug 2000-2023 air pollution index with: a) 500 hPa geopotential height, b) satellite net OLR, c) sea level air pressure, and d) sea surface temperature, all use same scale. Composite anomalies of top 20 air pollution months: e) zonal circulation (vector, max 5 m/s) and humidity (shaded) along 28.7S, f) meridional circulation (vector, max 2 m/s) and zonal wind (contour) along 32E, with vertical motion exaggerated and elevation profile.*

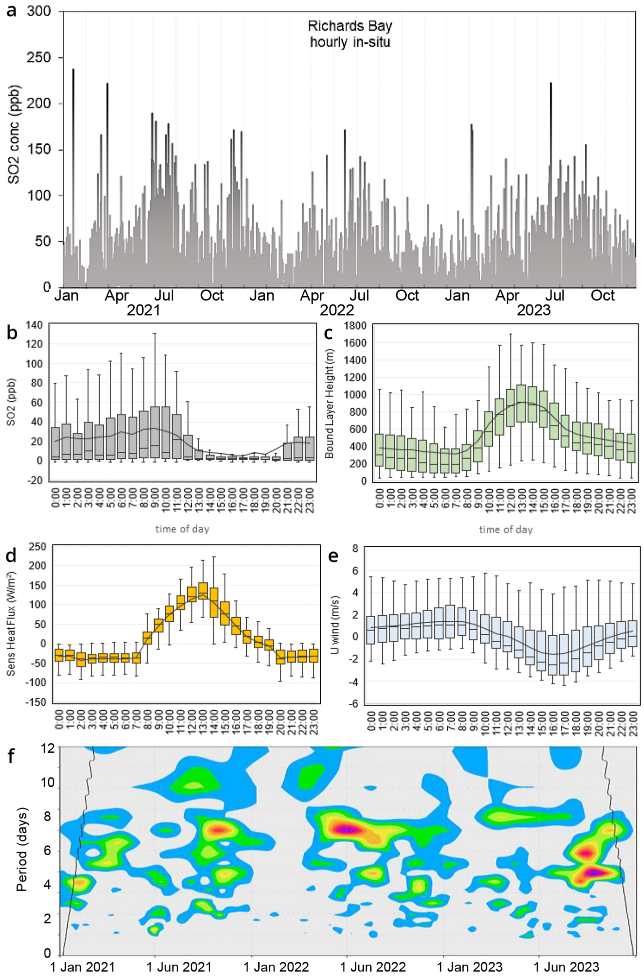

Figure 5: *a) In-situ measured hourly SO_2 concentration over three years. Mean diurnal cycle analysis during winter May-Aug 2021: b) SO_2, c) boundary layer height, d) sensible heat flux, e) east-west U wind, all times local. f) Daily dewpoint temperature wavelet spectra shaded > 90% confidence to reveal weather pulsing.*

Dispersion footprint and daily statistics

The winter mean maps of OMI satellite NO_2 concentrations (Fig 3c,d) reveal a footprint inland from Richard Bay that links westward to agricultural and industrial plumes from the interior. Marine air exhibits low concentrations but seldom penetrates westward during winter due to the prevailing offshore airflow. Local air quality does not exceed long-term health guidelines and is connected to nearby urban hotspots.

Figure 3e presents the daily time series of NO_2 and SO_2 which exhibits spikes due to the changeable weather. Summer values are suppressed by rainfall and unstable northeasterly winds and tend to remain below 10 ppb. During winter spells of dry weather and westerly winds daily values exceed 20 ppb. The time series have no significant trend, but year-to-year variability is evident and mainly related to the frequency of offshore (polluting) to onshore (clean) airflow.

Daily statistics are listed in Table 2b for 2004-2023. Dewpoint temperatures are associated with NO_2 and SO_2 (r = -0.35), followed by U_{925} wind and $PM_{2.5}$ (r = 0.23). Delta temperature is positively cross correlated with all air constituents (r = 0.18) and tells a story about the weather. During winters when transient frontal troughs are located to the west of Richards Bay ‘berg’ winds from the plateau descend, compress and dry the air. Nocturnal cooling creates a thermal inversion and shallow boundary layer that traps air pollutants, a universal phenomenon. In some winters the frontal troughs are followed by ridging high pressure cells that cleanse the air, but in other years the troughs are followed by sunny skies and continued poor dispersion. Those climatic differences are studied below.

Inter-annual variability

Using the monthly air pollution index (sum of time series in Fig 2a), point-to-field correlations illustrate the conditions distinguishing clean and polluted winters in Figure 4a-d. Warm sea temperatures in the west Indian Ocean cause a 500 hPa ridge over Madagascar 20°S, 55°E and a trough over the mid-latitudes 40°S, 40°E. A thermal wind pulls airflow over Richards Bay from the northwest, which is dry. Many of the features cover thousands of kilometers: the dry ridge extends from Namibia 15°S, 15°E to Mauritius 20°S, 60°E (Fig 4a,b), the surface low pressure extends from 35°-50°S, 30°-60°E (Fig 4c). The sea temperature pattern (Fig 4d) reflects the Indian Ocean dipole linked to slow moving ocean Rossby waves, equatorial winds and Pacific El Nino conditions (Kanyanga 2008, Nagura & McPhaden 2010, Jury 2018). Correlations are indicative of winter climate influences on local dispersion.

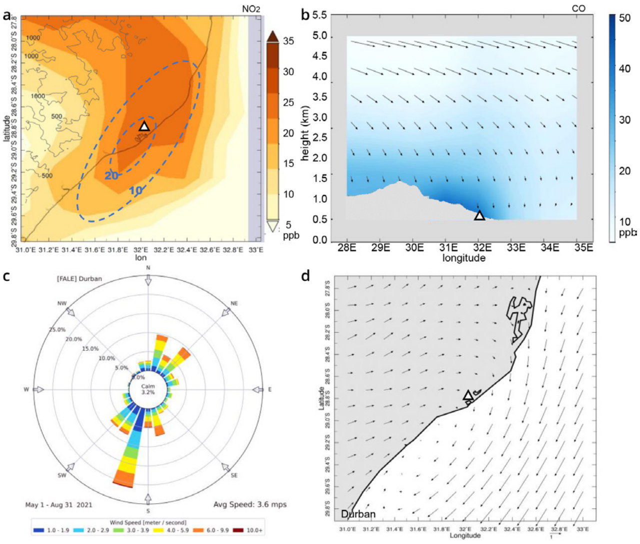

Figure 6: *Mean conditions during winter 2021. Satellite observed: a) NO_2 concentration map with $PM_{2.5}$ contours (dashed µg/m³), and b) CO height section on 28.7°S and zonal circulation (vector, max 8 m/s). c) wind rose at Durban, d) mean surface winds (vector, max 3 m/s) indicating circular airflow.*

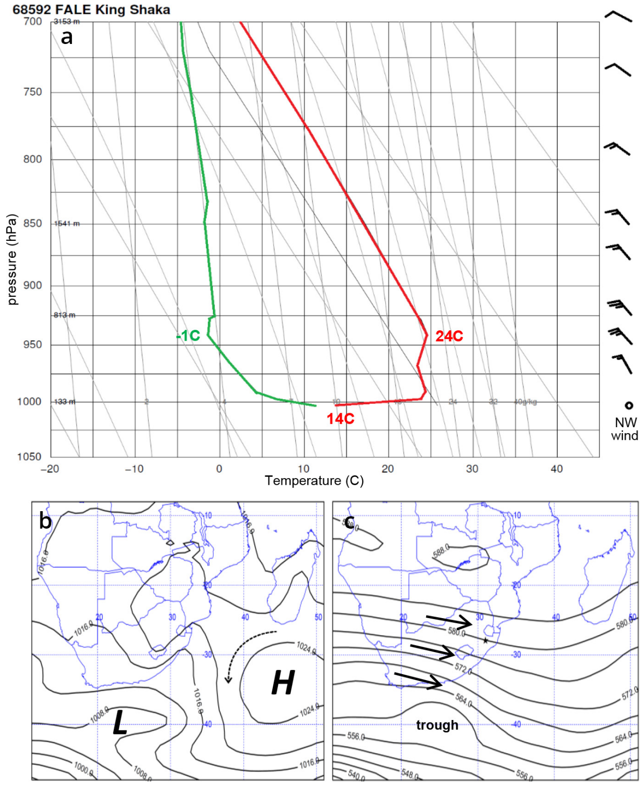

Figure 7: *Weather conditions at 02:00 16 June 2021: a) Durban radiosonde profile, b) sea level air pressure map (hPa), c) 500 hPa geopotential height map (m), with pressure cells and wind icons.*

Composite atmospheric circulation anomalies over Richards Bay during top 20 winter months with high air pollution are presented in Figure 4e,f. As expected, the zonal airflow is from west and reflects sinking motion with a dry characteristic below 500 hPa (~5.5 km) from 27°-33°E. The meridional airflow reflects poleward airflow, sinking motion below 500 hPa, and a strengthened upper level jet. A curious feature in these circulation patterns is the diffluent rising motion above 500 hPa. To the east of Richards Bay, enhanced humidity below 850 hPa remains over the Mozambique Channel under westerly winds. The downstream 'pull' by the thermal winds over the south Indian Ocean induces poor dispersion at Richards Bay.

Hourly statistics and diurnal cycle

Hourly time series of in-situ SO_2 from Jan 2021 to Dec 2023 is presented in Figure 5a, and temporal statistics for $PM_{2.5}$ and SO_2 during winter 2021 are listed in Table 2c. Spikes in the time series are attributed to diurnal oscillations amidst seasonal weather pulsing that brings rainfall. Particulates do not respond much to weather conditions except for higher U V wind correlations linked to turbulence. Boundary layer height and V wind are negatively cross-correlated with SO_2 (r = -0.22, -0.31). A shallow mixing depth and northerly winds induce poor dispersion at an hourly time scale. Amongst the weather variables, sensible heat flux and V wind are associated with boundary layer height (r = 0.43, 0.44) while U and V winds correspond (r = 0.70), merely indicating the SW-NE axis of coastal airflow.

The mean diurnal cycle averaged over winter 2021 is illustrated in Figure 5b-e. SO_2 reveals much higher values (30+ ppb) from 03:00 – 11:00 associated with nocturnal thermal inversions and shallow boundary layer height that traps pollutants below 400 m. Sensible heat fluxes are negative at night (-40 W/m²) and cool the lower atmosphere creating stability. By mid-day the sensible heat flux reaches 140 W/m² driving an alternation of U winds from landbreeze (+1 m/s at 07:00) to seabreeze (-2 m/s by 16:00). The back and forth airflow tends to recirculate pollutants, as seen in the next section on mapping winter 2021 dispersion.

Figure 5f reveals weather pulsing by applying wavelet spectral analysis to the time series of ERA5 dewpoint temperature. Oscillations of 4-8 days are statistically significant, and indicate the changeable nature of coastal weather at Richards Bay.

Mapping winter 2021 dispersion

Maps of NO_2 and CO concentration over Richards Bay area are presented in Figure 6a,b for May-Aug 2021. NO_2 shows a footprint of higher values (30 ppb) over and northeast of Richards Bay. Pollutants from local urban and industrial emissions appear linked to those from the Highveld to the northwest. NO_2 is derived from combustion and thus reflects emissions from local traffic, shipping, and agricultural burning. The CO height section identifies local surface emissions that produce the highest concentrations (40 ppb) below 2 km. The zonal circulation is dominated by upper westerlies that subside and weaken toward the surface. CO emissions from Durban infiltrate the Tugela Valley near 31E, according to the winter 2021 'wind rose' in Figure 6c, which shows a 22% frequency from SSW sector. 45% of the time the winter winds are < 3 m/s and non-dispersive. Similar characteristics have been reported at Richards Bay (Petzer et al 2008). One of the most interesting outcomes of this research is the circular nature of net surface airflow (Figure 6d). Winds from the northeast characterize the marine environment, while terrestrial winds are from the southwest. The centre of this

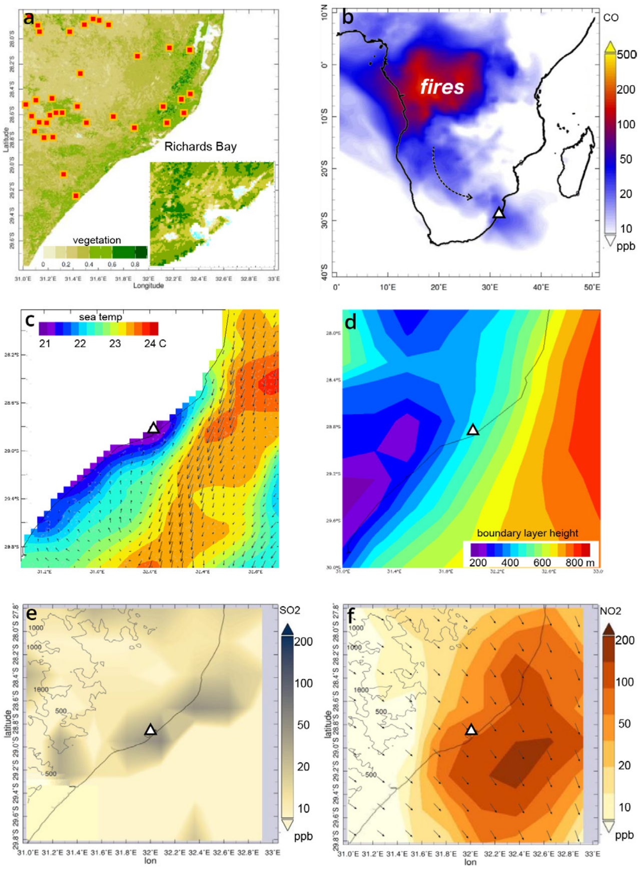

Figure 8: Environmental conditions during an air pollution event 15-17 June 2021: a) vegetation fraction and local fires ■ detected by satellite (inset zoomed), b) regional smoke plume CO concentration (log-scale), c) sea temperature and ocean currents, d) boundary layer height, e) SO_2 concentration (log-scale) with elevation contours, and f) NO_2 concentration and wind (vector, max 3 m/s). Triangle denotes Richards Bay.

rotary circulation is calm and overlies Richards Bay, resulting in little net transport during winter. Although recirculation may be inferred, the ever-present weather pulsing by atmospheric Rossby waves and their attendant high and low pressure cells forces an oscillation of this rotary airflow.

Air pollution episode: 15-17 June 2021

The daily time series of NO_2 and SO_2 (cf. Fig 3e) identified 15-17 June 2021 with high concentrations representative of a winter air pollution episode. Weather conditions are analyzed beginning with the 02:00 16 June 2021 radiosonde profile at Durban (Figure 7a) 150 km southwest of Richards Bay. The most striking feature was a 10°C nocturnal inversion from 0 – 60 m that decouples momentum transfer resulting in surface winds of 1 m/s. Thermal stability continued to 500 m, but airflow from NW increased to 12 m/s indicative of 'berg' winds. Dewpoint temperatures dropped to -1°C at 500 m due to the subsidence. A lapse rate of -9°C/km above the inversion corresponded with NW winds of 6 m/s. Weather maps at the surface and 500 hPa are illustrated in Figure 7b,c and show a trough to the southwest with a surface low pressure at 40°S, 23°E. A coastal low preceded the trough and was located over the Eastern Cape on 16 June 2021, while the surface Mascarene high was at 34°S, 45°E. The

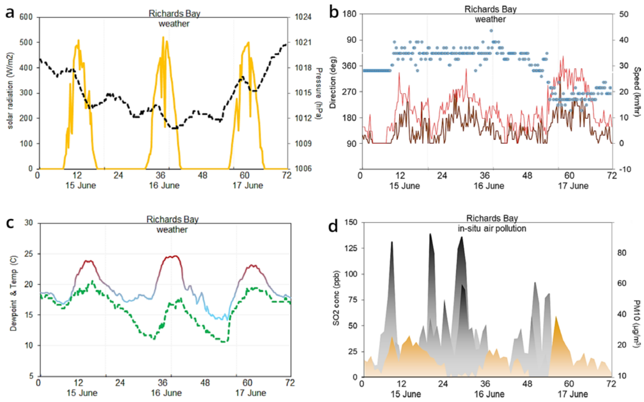

Figure 9: Hourly in-situ weather and air pollution records during an event 15 - 17 June 2021: a) solar radiation and air pressure reduced to sea level, b) wind direction (dots), speed and gust, c) air temperature and dewpoint, and d) in-situ SO_2 (grey) and PM_{10} concentration (brown).

upper westerly jet stream was 40 m/s, consistent with regional forcing seen in Fig 4a.

During this air pollution episode, local emissions were joined by smoke plumes from agricultural burning across Africa (Figure 8a,b). Fires over KwaZulu-Natal, the western Zambezi and the Congo Basin were entrained toward Richards Bay causing surface CO concentrations to rise. The boundary layer height was tilted by land-sea contrasts (Figure 8c,d): over the warm ocean current (Agulhas) values were 800 m, while over the cool Tugela Valley, values were 200 m. SO_2 and NO_2 concentration maps in Figure 8e,f suggest that the prevailing winter land breeze dispersed the Richards Bay emissions seaward.

In-situ station data were analyzed from 15-17 June 2021 in Figure 9a-d. Net solar radiation exhibited a diurnal cycle reaching at 500 W/m^2 at mid-day with dips from passing clouds. The air pressure of 1019 hPa on the 15th declined to 1011 hPa by the 16th then recovered to 1021 by the 17th, all indicative of passage by a coastal low associated with the mid-latitude trough. Northeasterly winds fluctuated above 10 km/hr on the 15th and 16th then became calm and switched to southwesterly on the 17th. Air temperatures warmed to 24°C each afternoon and declined to 15°C on the evening of the 16th. Dewpoint temperatures might be expected to remain steady but have diurnal cycling, with values of 11°C in the early morning of the 16th and 17th. These indicate 'berg' winds join the nocturnal land breeze and promote radiation cooling during air pollution episodes. Hourly in-situ SO_2 and PM_{10} concentrations revealed spikes above 100 ppb and 20 ug/m^3. These were out-of-phase: particulates rose during the day, whereas SO_2 rose at night. By the 17th south-westerly winds had dispersed SO_2 away from the monitoring stations and toward the city.

Particulate episode: 4-5 July 2022

Unlike trace gases, $PM_{2.5}$ and PM_{10} records do not exhibit a clear annual cycle. Long-range transport of Kalahari dust and Zambezi smoke plumes join urban emissions from the Highveld during dry spells when troughs maintain north-westerly airflow. These features appear during a case study 4-5 July 2022 in Figure

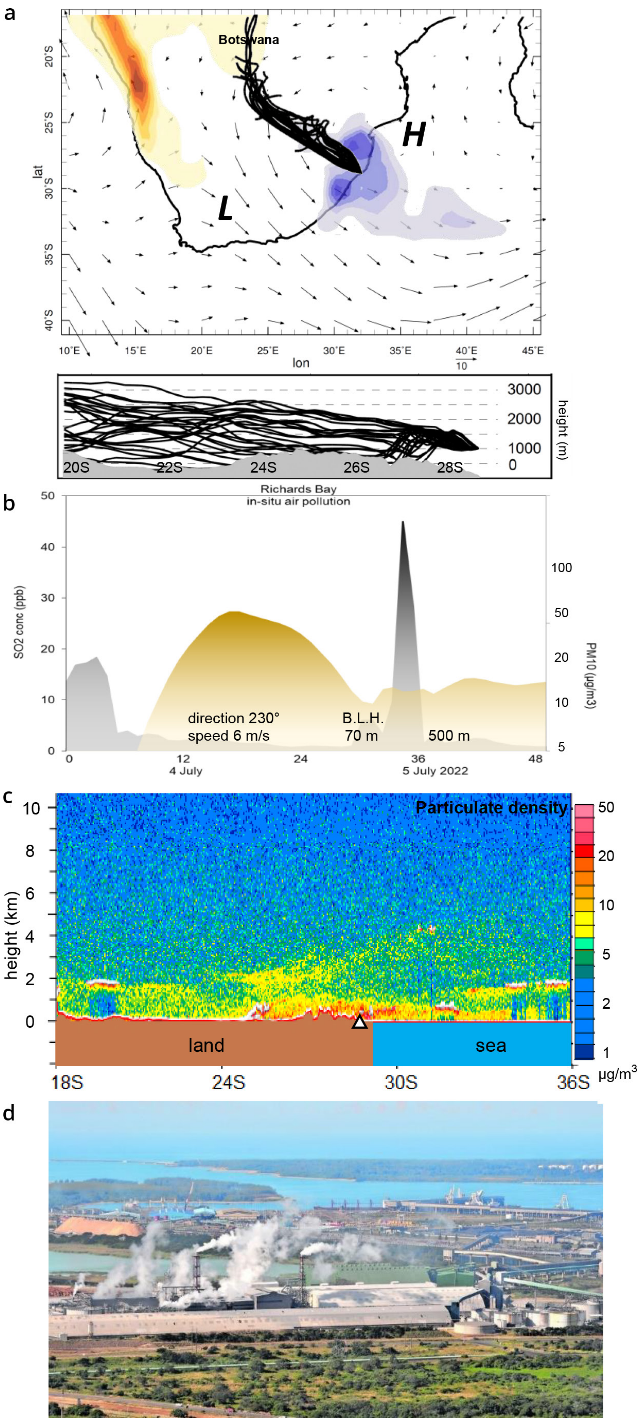

Figure 10: *a) HYSPLIT back trajectories arriving at Richards Bay 4-5 July 2022 (map and side view), MERRA2 dust (brown) and smoke (blue) plumes and 850 hPa wind (vectors). b) Hourly in-situ SO_2 (grey) and PM_{10} (brown) on 4-5 July 2022, c) N-S height section on 31.8E of satellite lidar backscatter indicating particulate density (log-scale) at 22:00 on 4 July 2022, d) aerial photo of Richards Bay industrial zone and harbour.*

10a. HYSPLIT back-trajectories arrive from the 1-3 km layer over Botswana, gathering a variety of particulates along the way.

Local measurements (Figure 10b) confirm high particulate concentrations on the afternoon of 4 July as southwest winds of 6 m/s spread coal dust from the harbour. ERA5 weather data indicate warm, dry, turbulent conditions with sensible heat fluxes of 150 W/m^2 and boundary layer height of 760 m. The CALIPSO satellite height section (Figure 10c) reveals a dense layer of particulates below 1 km and plumes slanting upward from land to sea. Local measurements contain a 45 ppb spike of SO_2 at Richards Bay at 10:00 on 5 July 2022, indicating the sudden vertical spread of elevated plumes as boundary layer height grew from 70 m at sunrise to 500 m by noon. The mixture of distant and local emissions add to the burden of respiratory health, and tend to accumulate under the same weather conditions.

Conclusions

This study has deepened our understanding of climate and weather conditions underlying Richard Bay's air pollution dispersion, based on satellite and in-situ measurements assimilated by sophisticated models. Near-surface concentrations of trace gases and particulates reach high concentrations under dry stable 'berg' winds. Temporal records of CO, NO_2, O_3, $PM_{2.5}$, and SO_2 (2000-2023) exhibit no trend and short-term dose exceedances of individual pollutants are rare and confined to winter mornings.

Regional point-to-field correlation maps of the Richards Bay winter air pollution index determined that warming in the west Indian Ocean accelerates the jet stream over Madagascar and pulls smoke- and dust-laden north-westerly winds across the South African plateau toward the coast of KwaZulu-Natal. A case study 15-17 June 2021 revealed a 10°C thermal inversion caused by a negative sensible heat flux of -40 W/m^2 during the night, leading to SO_2 concentrations above 100 ppb in the morning along the main access road (28.8°S, 32°E). In contrast, summer weather is characterized by turbulent mixing and rainfall that cleanse the air. At daily and hourly time scales, low dewpoint temperature, boundary layer height, and northwest wind best indicate poor air quality. Winter dry spells that accumulate air pollutants can be anticipated by local health services to prepare for increased respiratory impacts.

Recommendation

The proximity of Richard Bay's industrial zone to the scenic waterfront (Figure 10d) makes it difficult to conceive a mitigating strategy that could put the city on a more environmentally friendly path. Although coal exports will decline as the world seeks to limit greenhouse warming, the current use of road transport for delivery to the harbour has caused soot build-up on city streets, leading to respiratory impairment and lost productivity. Coal delivery by rail and transfer to ships on the southwest side of the harbour seems a better option.

Acknowledgements

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drawn from websites: NASA-Giovanni, KNMI Climate Explorer, IRI Climate Library, APDRC-Hawaii, Univ Wyoming radiosonde, IEM wind rose, and Wundermap. A spreadsheet is available on request.

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Research article

Longitudinal analysis of annual $PM_{2.5}$ concentration variations in Blantyre City, Malawi

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Abstract

This study presents current levels of fine particulate matter, with aerodynamic diameter of less than 2.5 micrometre ($PM_{2.5}$) in the city of Blantyre, Malawi measured between June 2021 to May 2022. $PM_{2.5}$ measurements were done in 18 different locations (spanning greater than 2 km apart) using Dylos DC1100 PRO Laser Particle Counter (2018 model). The sampling points were; 3 school campuses, 3 hospitals, 3 industrial areas, 3 open markets, 3 residential areas, and 3 commercial/ business centres (CBC) of Blantyre. $PM_{2.5}$ monitoring was conducted between 10:00-12:00 hours and 15:00-17:00 hours local time. The results showed that the hourly mean $PM_{2.5}$ concentrations (µg/m^3) for the 10:00-12:00 time period were; 43 ± 23 µg/m^3 for school campuses, 35 ± 16 µg/m^3 for hospitals, 62 ± 38 µg/m^3 for industrial areas, 44 ± 26 µg/m^3 for markets, 40 ± 21 µg/m^3 for residential areas and 35 ± 16 µg/m^3 for CBC. The results showed that the hourly mean $PM_{2.5}$ concentrations (µg/m^3) for the 15:00-17:00 time period were; 38 ± 22 µg/m^3 for school campuses, 34 ± 18 µg/m^3 for hospitals, 57 ± 37 µg/m^3 for industrial areas, 42 ± 25 µg/m^3 for markets, 36 ± 23 µg/m^3 for residential areas and 34 ± 18 µg/m^3 for CBC. Significant increases of $PM_{2.5}$ levels were observed in school campuses, residential areas and CBC during the months of June-October, which are windy and drier. On the other hand, lowest concentration of $PM_{2.5}$ was observed during the warm season (November-March) across the sampling locations over Blantyre. Based on these findings, this study recommends further investigation of long-term concentration of $PM_{2.5}$ in Blantyre city because it is hazardous and likely to cause health implications to the local population. Furthermore, interventions should be sought to reduce $PM_{2.5}$ concentration in the city.

Keywords

Air Quality, Air Pollution, Concentration, Particulate Matter, Environment

Introduction

Continuous air quality monitoring and evaluation are critical for protecting public health and the environment, enforcing regulations, and making informed policy decisions. Industrialisation and technological growth are expected to continue in Africa; as such, it is also expected that air pollution will continue to rise (Fisher et al., 2021). Exposure to air pollution causes harm and discomfort to humans or other living organisms. It damages the natural environment and the atmosphere (Okello et al., 2023). Particulate matter (PM) consists of a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air (Leon et al., 2019). Particulate matter ($PM_{2.5}$) are particles with sizes less than or equal to 2.5 micrometers. Concentration changes of $PM_{2.5}$ are originated from both natural and anthropogenic sources (Cachon et al., 2023). Some of the natural sources include; volcanic emissions, forest fires, pollen scattering and sand storms (Xu et al., 2020).

Anthropogenic sources generally emit much higher levels of $PM_{2.5}$ than natural sources (Jahandari, 2020). Anthropogenic activities have resulted into many sources of $PM_{2.5}$ on the Earth (Triki and Said, 2021). Some of the $PM_{2.5}$ sources are; factories, burning of fossil fuels in engines like those of automobiles, and chemical substances created in the process of waste disposal (Osipov et al., 2022). Generally, $PM_{2.5}$ of anthropogenic origin significantly exceeds the natural background. Most of these anthropogenic sources of $PM_{2.5}$ are present in Blantyre city (Kaonga et al., 2021).

Finer particles like $PM_{2.5}$, can settle in the bronchi and lungs (Ahmed et al., 2022). $PM_{2.5}$ can cause health problems and contribute to the risk of development of respiratory and cardiovascular disease, including lung cancer. $PM_{2.5}$ are small enough to enter deep into the lungs and can cause respiratory and cardiovascular problems, including asthma, bronchitis, and even heart attacks (Pai et al., 2022). Long-term exposure to high levels of $PM_{2.5}$ can increase the risk of premature death (Nilsa, 2007; Toro-Heredia, Jirau-Colón and Jiménez-Vélez, 2021). High levels of $PM_{2.5}$ can also harm the environment, including reducing visibility, damaging crops and forests, and contributing to climate change (Sturm, 2020).

Many countries have regulations in place to limit the amount of $PM_{2.5}$ in the air to protect public health and the environment. From Malawi Standard on Industrial Emissions (MS 737:2011), the limit values for $PM_{2.5}$ concentration in ambient air are 25 µg/m^3 and 8 µg/m^3 for 24 hour and annual average concentrations, respectively. The focus on population–oriented monitors stems from health information that forms the basis for the annual $PM_{2.5}$ standard. This information relates from area-wide health statistics to area-wide air quality (MBS, 2017). The current WHO guidelines state that annual average concentrations of $PM_{2.5}$ should not exceed 5 µg/m^3, while 24-hour average exposure should not exceed 15 µg/m^3 (World Health Organization, 2021).

There has been no scientific study of $PM_{2.5}$ using monitors that capture data in real time in Blantyre. Spatial and temporal variation of $PM_{2.5}$ concentrations in Blantyre city or evaluation of the effectiveness of air quality policies has never been reported (Nyasulu et al, 2023). Blantyre city has high vehicle and motorcycle traffic in its main roads, many manufacturing industries and a lot of construction activities (National Statistical Office, 2019).

Monitoring of $PM_{2.5}$ levels in Blantyre city could also be beneficial in several ways. Citizens can benefit from $PM_{2.5}$ monitoring by being aware of the air quality in their community, which can help them take measures to protect their health. For example, people with respiratory conditions can take steps to avoid outdoor activity during periods of high $PM_{2.5}$ levels. Also, $PM_{2.5}$ monitoring can provide researchers with valuable data for studying the effects of air pollution on human health and the environment. By analysing the data, researchers can identify trends and patterns in $PM_{2.5}$ levels and their impact on various populations. Furthermore, $PM_{2.5}$ monitoring might be crucial for the government to develop and implement effective policies and regulations for air quality management. The data collected can help the government and regulatory bodies evaluate the effectiveness of existing policies and make informed decisions about future policies to protect public health and the environment. The data collected for $PM_{2.5}$ monitoring can be used by businesses to make informed decisions about their operations. For example, companies in Blantyre could use the data to determine the best location for a new factory or to develop strategies to reduce their impact on air quality. This necessitated this study which determined $PM_{2.5}$ pollution at 18 different locations with varying background activities in Blantyre city, Malawi.

Materials and methods

Study area

Malawi is a landlocked country located in South-Eastern Africa with a dense population. It is bordered by Tanzania to the North, Zambia to the North-West with Mozambique joining it on the east, south and west. The country has a tropical climate consisting of a dry season lasting from May to October and a wet (rainy) season extending from November to April.

Blantyre city is the urban centre of Blantyre District in Malawi, which is found in the southern region of this nation at −15°29′59.99″S, 35°00′0.00″E and has an area of 240 km^2. With a population of about 1 million with a growth rate of 3.5%, Blantyre is a commercial and industrial city located in the southern region of Malawi (National Statistical Office, 2019). It has an estimated elevation of 1039 meters above sea level which is significant in moderating the climate which is tropical. In terms of the climate, like most of the districts in Malawi, Blantyre has two dominant seasons during the year namely the dry and wet seasons. The wet season spans from November to May and the rest of the year is dry, with temperatures rising until the next rains arrival. 20.7°C is the average temperature in Blantyre, and approximately 1086 millimeters of rain is received each year, a typical characteristic of Malawian weather as shown Figure 1 (Zandbergen, 2022).

This study aimed at measuring the concentration changes of $PM_{2.5}$ in school campuses (SCH), hospitals (HSP), industrial areas (IND), markets (MKT), residential areas (RES) and commercial and business centre (CBC) of Blantyre City, in Malawi. A total of 18 locations with varying pollution sources, such as dusty roads, industrial emissions, and residential combustions, were selected for $PM_{2.5}$ monitoring. The chosen locations were at a distance of not less than 2 km from each other so as to give an overview of the entire city. The map showing $PM_{2.5}$ measurement locations selected in Blantyre city has been presented in Figure 2 below. These sites have higher number of people present during daytime in Blantyre.

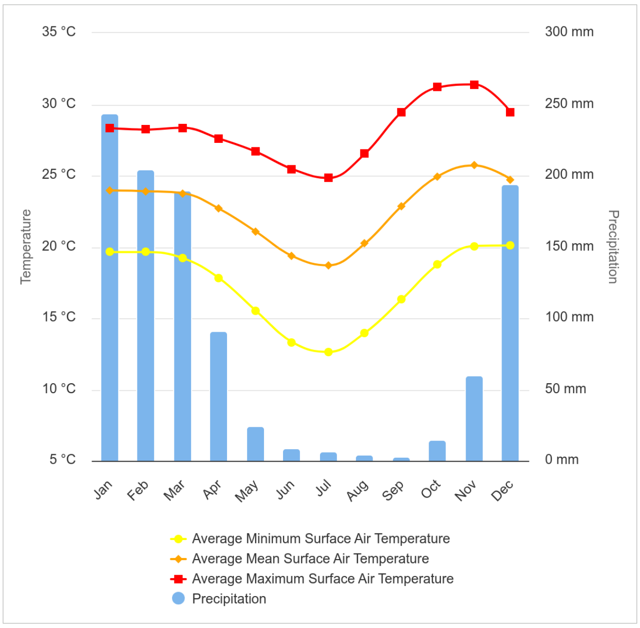

***Figure 1:** Monthly climatology of average minimum surface air temperature, average mean surface temperature, average maximum air temperature and precipitation 1991-2020 (Data source: Malawi Department of Climate Change and Meteorological Services, 2024)*

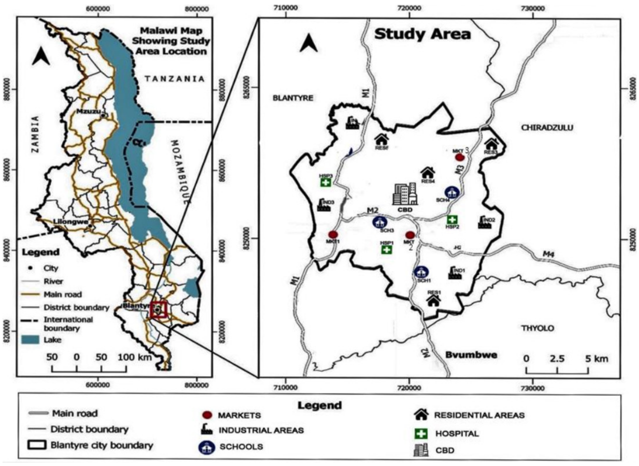

Figure 2: *Map of measurement locations of $PM_{2.5}$ in Blantyre city, Malawi.*

Instrumentation

In all the 18 monitoring locations, active mobile PM monitors (Dylos DC1100 PRO Laser Particle Counters of 2018 model, manufactured by Dylos Corporation, USA) were used to measure the concentration of $PM_{2.5}$. The particulate monitoring equipment were placed at 1.5 m above ground level. The position of the Dylos instruments at a sampling height of 1.5 m, was a representation of a typical breathing level, to simulate human exposure to $PM_{2.5}$ as shown in Figure 3. An hourly average value was recorded. The measurements were made twice on the same day; one in the morning (10:00-12:00 hours) and another in the afternoon (15:00-17:00 hours). There is a lot of human mobility and industrial activities happening during 10:00-12:00 and 15:00-17:00 time intervals in Blantyre city, which could lead to emission of air pollutants including $PM_{2.5}$ (Thulu, 2023). This $PM_{2.5}$ measurement exercise took place from 1 June 2021 up to 31 May 2022 on a daily basis.

Figure 3: *Monitoring setup at one of the schools (Credit: Kingsly Kabango).*

Airborne PM at can be measured quickly and precisely using laser particle counters. The Dylos DC1100 PRO PC Interface option allows one to download the air quality data to a PC for graphing and analysis. Vyas et al, (2016) and Dlyos Corporation (2016), comprehensively explain the details and a description of the Dylos DC1100's specifications and site theory of use. The Dylos DC1100 PRO Laser Particle Counter operates based on the principle of light scattering. The device emits a laser beam into the air sample. As the laser beam travels through the air, it interacts with particles present in the sample. When a particle passes through the laser beam, some of the light is scattered in various directions. The intensity and pattern of the scattered light depend on the size and characteristics of the particle. The Dylos DC1100 PRO has a light detector that captures the scattered light. Then, the device processes the data received from the light detector to determine the number and size distribution of particles in the air. The device categorizes particles based on their size, and for $PM_{2.5}$ measurements, it specifically focuses on particles with a diameter of 2.5 micrometers or smaller. Thereafter, the processed information is then displayed on the device's screen or output to a connected system, providing real-time data on particle concentrations, including $PM_{2.5}$ levels.

The monitors were calibrated for accuracy and reliability. Calibration was deemed crucial to ensure accurate measurements with the Dylos instruments used in this study. The manufacturer's guidelines for calibration, which involves comparing the instrument's readings to a reference monitor were done at Malawi Bureau of Standards (MBS) at the commencement of the study. The Dylos DC1100 PRO Laser Particle Counters were calibrated with reference monitor GRIMM reference instrument. High reproducibility level with R^2 value between 0.99 and 1 were attained between the 1-hour PM concentrations generated by all Dylos DC1100 PRO Laser Particle Counter sensors used during 2-day calibration exercise at Malawi Bureau of Standards. The R^2 value of concentration achieved are acceptable by Malawi Bureau of Standards, such that the Dylos DC1100 PRO Laser Particle Counter could indicate consistence and similarity in the readings. The WHO guidelines on air quality standards and guidelines on $PM_{2.5}$ monitoring were used. The guidelines provide recommendations on monitoring equipment, sampling strategies, and data analysis methods (WHO, 2021).

Data analysis

Completeness, and consistency of the monitored $PM_{2.5}$ values was done at the end of every month using R-Instat Version 0.7.9.42. This ensured that there are no gaps or missing data in the monitored records. $PM_{2.5}$ concentration values were then analysed using appropriate statistical methods. This involved calculating the monthly average concentration from daily averages of $PM_{2.5}$ over a monitored period and identifying trends over time. Mann Kendall test for trend was carried out in R programming language and environment to determine trends of average $PM_{2.5}$ concentration levels at all the study sites. This helped to statistically check the significant trends in changes for $PM_{2.5}$ concentration levels in school campuses, hospitals, residential areas, CBC and markets. The $PM_{2.5}$ concentration levels were subjected to a trend statistical analysis from June to September, September to December, and December to May. Analysis of $PM_{2.5}$ during these periods in Malawi is crucial due to the country's distinct seasonal climate patterns. These periods coincide with significant weather transitions, including the windy/gusty, dry and wet seasons in Malawi. Therefore, doing $PM_{2.5}$ statistical trend analysis during these periods provides valuable insights into how seasonal variations impact air quality in Blantyre.

Results and discussion

Supplementary Table S1 and Table S2 highlight the monthly captured data for all the monitoring sites. Figures 4 and 5 show an overview of the mean comparison of $PM_{2.5}$ concentrations per category of sites for the 12 months (1 year). High values of $PM_{2.5}$ concentrations were observed in industrial sites (62 ± 38 µg/m^3) followed by market areas (44 ± 26 µg/m^3) for the 10:00-12:00 time period. Gas emissions and land construction activities in these sites could be attributed to high values of $PM_{2.5}$ concentrations. There was a lot of dust in the markets during drier months. Also, open fire cooking using firewood was observed in the market area. This could also lead to high $PM_{2.5}$ concentrations. From Table S3 and Table S4, it can be seen that during August, many of the sites had higher $PM_{2.5}$ concentrations during 10:00-12:00 and 15:00-17:00. It was also observed that $PM_{2.5}$ concentrations were much lower between 15:00-17:00 for January and February in all sites. It was also observed that there were site specific sources and activities that contributed to particulate loadings in industries and hospitals (open fire cooking areas). At all sites, it was observed that the $PM_{2.5}$ peak gradually increased, and then decreased for days with low prevailing winds for the morning monitored hours. This was somewhat different during 15:00-17:00, mostly for wet months for hospitals, schools and residential areas. This agrees with the fact that meteorological factors such as wind affect $PM_{2.5}$ concentrations e (Hou, 2023; Pardo 2023).

In a city like Blantyre, industries and open markets might have had higher levels of $PM_{2.5}$ compared to schools and hospitals due to the concentration of activities that produce particulate matter. Industries typically emit pollutants from manufacturing processes, machinery, and combustion of fuels, while open markets may generate dust from vehicular traffic, food preparation, and waste disposal. These activities release pollutants directly into the surroundings, which could also have contributed to higher levels of $PM_{2.5}$. In contrast, schools and hospitals registered lower $PM_{2.5}$ concentrations. This could be due to measures put in place to restrict outdoor activities, resulting in lower $PM_{2.5}$ concentrations within their premises.

Residential areas and Blantyre CBC experienced moderate levels of $PM_{2.5}$. This might be due to a combination of factors. In residential areas, sources of particulate matter include vehicular emissions from nearby roads, household combustion activities such as cooking and heating, as well as dust from construction

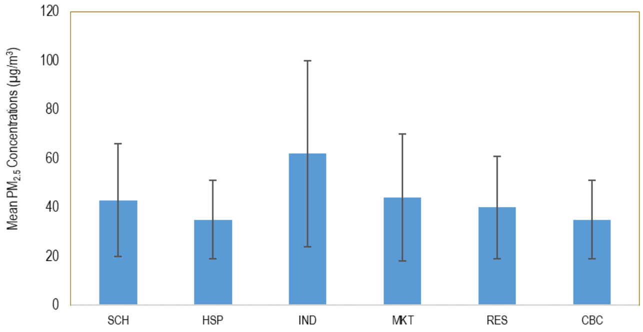

Figure 4: *10:00-12:00 hours mean $PM_{2.5}$ concentration across the sites (bars indicate standard deviations).*

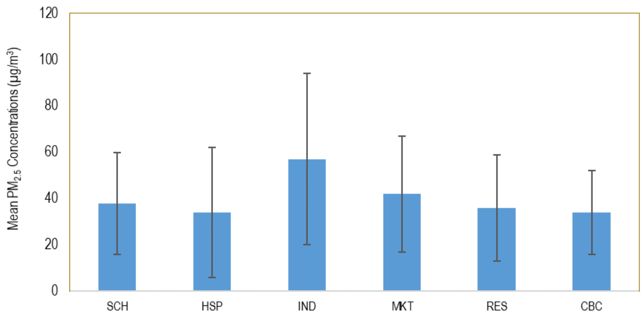

Figure 5: *15:00-17:00 hours mean $PM_{2.5}$ concentration across the sites (bars indicate standard deviations).*

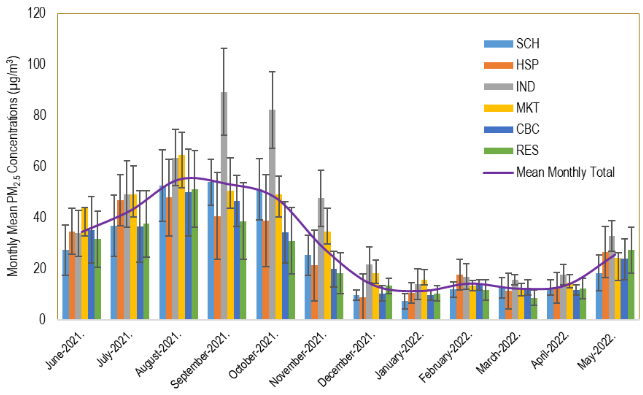

Figure 6: *10:00-12:00 hours monthly mean $PM_{2.5}$ concentration across the sites (bars indicate standard deviations).*

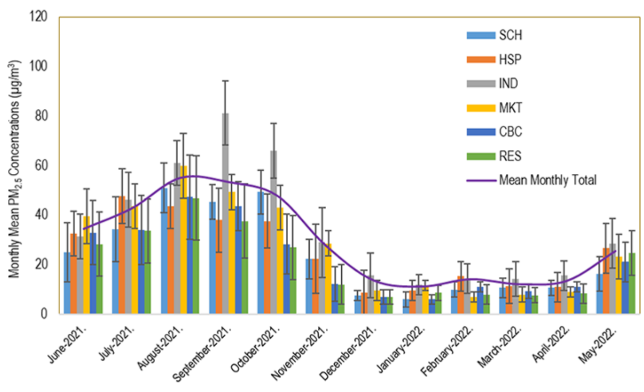

Figure 7: *15:00-17:00 hours monthly mean $PM_{2.5}$ concentration across the sites (bars indicate standard deviations).*

and landscaping. Similarly, CBC often have high traffic volumes and commercial activities which contribute to $PM_{2.5}$ emissions. While these areas may have some regulations in place to mitigate pollution, the low density of human activities might also have contributed to low $PM_{2.5}$ concentrations. Additionally, tall buildings in CBC may trap pollutants, leading to moderate $PM_{2.5}$ concentrations.

Figure 6 and 7 show the comparison of $PM_{2.5}$ concentrations across each group per month. The results showed that the monthly mean $PM_{2.5}$ concentrations (μg/m^3) were higher between the months of July to October with the highest observed in the month of September during for the 10:00-12:00 time period and 15:00-17:00 time period. Similarly, the results showed that the monthly means of $PM_{2.5}$ concentration (μg/m^3) was lower in the months from December to April. This can also be seen in Supplementary Table S2.

The monthly mean ambient concentrations of $PM_{2.5}$ levels across the 18 monitored sections of Blantyre city are shown in Figures 8 to 19. These give a detailed understanding of how $PM_{2.5}$ concentration varied among the sampling sites for the twelve months of the monitoring period.

In schools, high $PM_{2.5}$ values between 10:00-12:00 were observed in the month of September. The $PM_{2.5}$ values were almost constant between the months of November and May, with a start of an increment in June (Figure 8). During 15:00-17:00, high $PM_{2.5}$ values were recorded in the month of October. A sharp decrease was observed in November, then the $PM_{2.5}$ were constant from December to May (Figure 9). A sharp rise in $PM_{2.5}$ was observed in the month of June.

In hospital sites, high $PM_{2.5}$ values between 10:00-12:00 were observed in the month of July to October, with the highest values in June. The $PM_{2.5}$ values were almost constant between the months of December and April, with a start of an increment in May (Figure 10). During 15:00-17:00, high $PM_{2.5}$ values were recorded in the month of June as well. A sharp decrease of $PM_{2.5}$ was observed in November, and then the $PM_{2.5}$ values were constant from December to April (Figure 11). A sharp rise in $PM_{2.5}$ was in the month of May. During February 2022, there was a road rehabilitation near HSP 3. This could be the reason in rising $PM_{2.5}$ for this site during this month.

For industrial sites, high $PM_{2.5}$ values between 10:00-12:00 were observed in the months of September to October. There was a big drop of $PM_{2.5}$ in November. The $PM_{2.5}$ values were almost constant between the months of December and April, with a start of an increase in May (Figure 12). Site 3 of industrial area had the highest particulate loadings (97 μg/m^3) starting at 10:00 as compared to the remaining site 1 and site 2. This indicates that there might be a specified or defined source contributing to increased concentration at this site. During 15:00-17:00 hours,

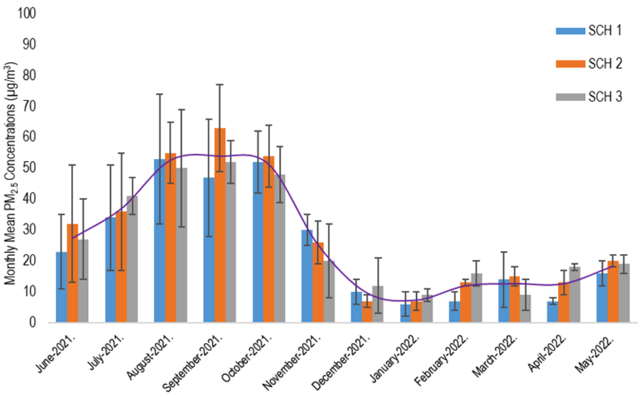

***Figure 8:** 10:00-12:00 hours monthly mean ambient $PM_{2.5}$ concentration for schools (bars indicate standard deviations).*

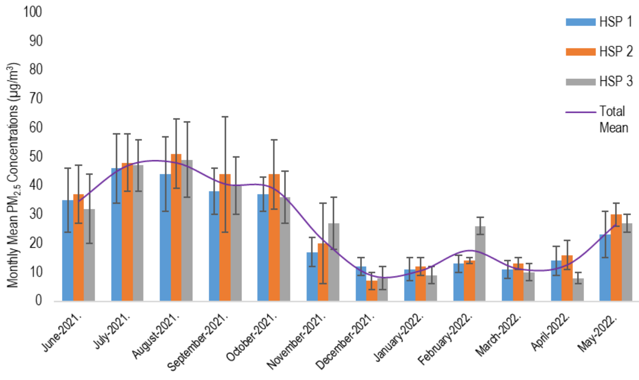

***Figure 10:** 10:00-12:00 hours monthly mean ambient $PM_{2.5}$ concentration for hospitals (bars indicate standard deviations).*

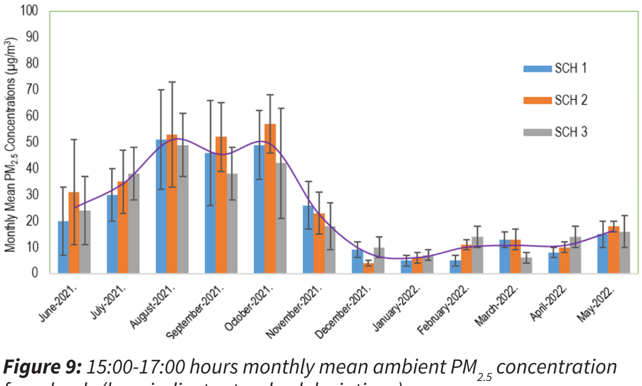

***Figure 9:** 15:00-17:00 hours monthly mean ambient $PM_{2.5}$ concentration for schools (bars indicate standard deviations).*

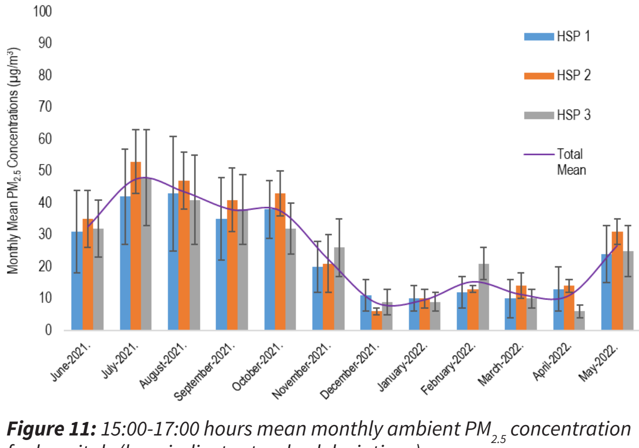

***Figure 11:** 15:00-17:00 hours mean monthly ambient $PM_{2.5}$ concentration for hospitals (bars indicate standard deviations).*

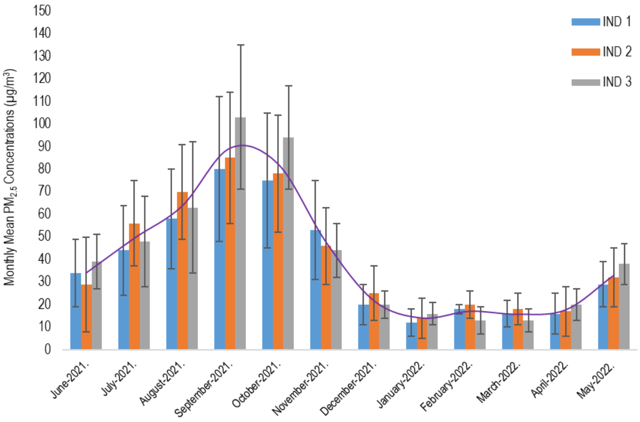

Figure 12: *10:00-12:00 hours monthly mean ambient $PM_{2.5}$ concentration for industrial areas (bars indicate standard deviations).*

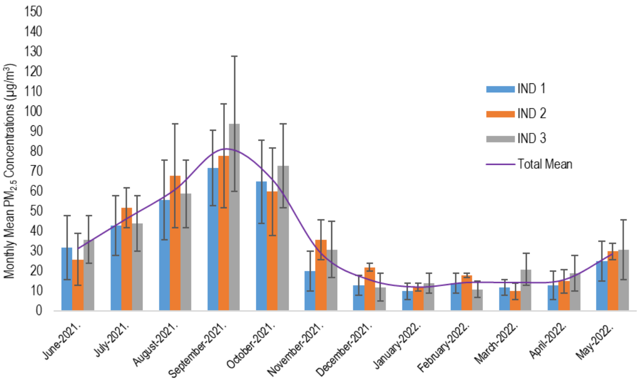

Figure 13: *15:00-17:00 hour monthly mean ambient $PM_{2.5}$ concentration for industrial areas (bars indicate standard deviations).*

high $PM_{2.5}$ values were recorded in the month of September. A sharp decrease of $PM_{2.5}$ was observed in November, then the $PM_{2.5}$ values did not fluctuate much from December to April (Figure 13). A rise in $PM_{2.5}$ was observed in June 2021. Between the month of August and September there was a lot of heavy vehicles moving in and out of cement factory at IND 1. This could be the reason in rising $PM_{2.5}$ for this site during these months. Thereafter, another route was opened out of the factory, which could have reduced the $PM_{2.5}$ at the monitoring point.

For market sites, high $PM_{2.5}$ values between 10:00-12:00 were observed in the month of August. Low levels of $PM_{2.5}$ were observed in November and then, there was a rise of $PM_{2.5}$ in June. The $PM_{2.5}$ values were almost constant between the months of December and April (Figure 14). During 15:00-17:00 hours, high PM values were recorded in the month of August. $PM_{2.5}$ values decreased in November while it remained constant from December to April (Figure 15). A rise in $PM_{2.5}$ was observed in the month of July. During the month of September of 2021, it rained for 3 days, which might be the reason in the decrease of $PM_{2.5}$ at MKT 1 during this month. Also, during January of 2022, there was a dry spell for most of the days in Blantyre, which could be the cause of a build-up in $PM_{2.5}$ as observed at MKT 1 and MKT 3. The drier the soils, the higher the chances of dust emissions (Erdenebayar, 2016).

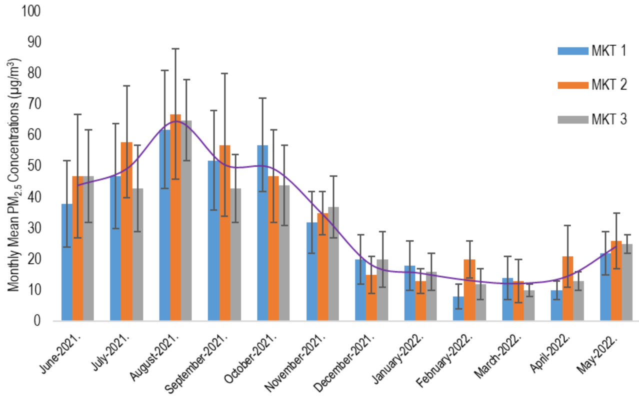

Figure 14: *10:00-12:00 hours monthly mean ambient $PM_{2.5}$ concentration for markets (bars indicate standard deviations).*

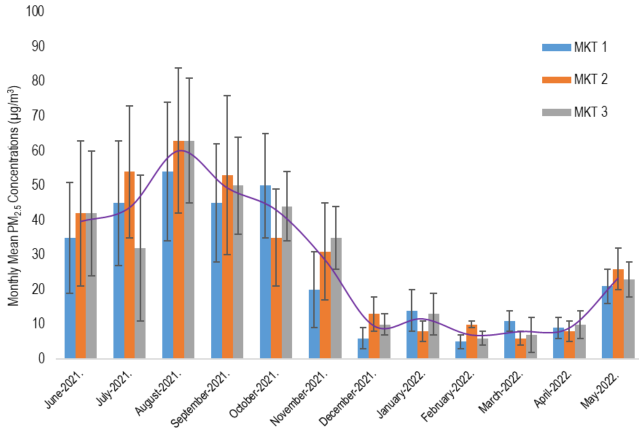

Figure 15: *15:00-17:00 hours monthly mean ambient $PM_{2.5}$ concentration for markets (bars indicate standard deviations).*

In residential areas, high $PM_{2.5}$ values between 10:00-12:00 were observed in the month of August. A drop of $PM_{2.5}$ was observed in October. The $PM_{2.5}$ values were almost constant between the months of December and April, with a start of increment in May (Figure 16). During 15:00-17:00, high $PM_{2.5}$ values were recorded in the month of August. A sharp decrease was observed in October, then the $PM_{2.5}$ remained constant from December to April (Figure 17). A rise in $PM_{2.5}$ was seen in the month of June. Vegetative cover was poor around RES 3, and it is densely populated as compared to RES 1 and RES 2. This could be a possible reason why RES 3 had higher $PM_{2.5}$ as compared to RES 1 and RES 2.

Lastly, at the sites of Blantyre CBC, high $PM_{2.5}$ values between 10:00-12:00 were observed in the month of August. The PM values were almost constant between the months of November and April, with a start of an increase in May 2022 (Figure 18). During 15:00-17:00 hours, high $PM_{2.5}$ values were recorded in the month of August to September. There was a $PM_{2.5}$ decrease in October, then it remained unchanged from December to April (Figure 19). There was a rise in $PM_{2.5}$ in the last days of the month of May 2022. In July 2021, $PM_{2.5}$ decreased at CBC 3. The road passing through the sampling point was closed, due to building rehabilitation which was happening ahead of the sampling point. This reduction in mobility of people and vehicles could be the cause in a decrease in $PM_{2.5}$ at this site.

The results indicate that $PM_{2.5}$ concentrations can be grouped into two periods based on seasons, namely, November-April and May-October. The $PM_{2.5}$ concentrations were lower during the period November-April. This can be attributed to the fact that these are wet months as shown in Figure 1. Generally, there was more vegetative cover within the city during these months due to rains (Mawenda, 2020). Rains and vegetation are known to filter particulate matter from the atmosphere (Przybysz, 2019). In Blantyre, the dry season ranges from July to October and it tends to be windier than the wet months. This leads to more dust storms within the city. This could be a contributor to the high $PM_{2.5}$ values observed during these months. Mapoma et al. (2014) also reported that there are a lot of human activities during this period such as; roads and buildings construction, waste disposal, burning of crop residues and industrial emissions which are known to release large amounts of PM in the air in Blantyre.

The highest $PM_{2.5}$ concentration was recorded at industries and markets as shown in Supplementary Table S3. For example, for industry and markets, the highest $PM_{2.5}$ concentration values observed in August were 138 µg/m³ and 135 µg/m³, respectively. The observed exceedances at these sites may be attributable to the direct exposure to emissions from fuel combustion and dusty storms (Kaonga et al., 2021). Low levels of $PM_{2.5}$ in schools and hospitals were likely due to less emissions from domestic fuel combustion and good vegetative cover, among others. It should be noted that the monitors were placed outdoors. At these sites, it was observed that fuel combustions happened outdoors as well, such as women (guardians) cooking using firewood outside the hospital premises. From this study, it was clear that there are still significant higher concentrations of $PM_{2.5}$ over the industrial areas, markets and residential areas within Blantyre.

The Mann-Kendall test revealed that significant trends were observed for $PM_{2.5}$ levels at school campuses, industries, residential areas, and CBC while markets and hospitals did not show any significant trend (Table 1). Mann Kendall's Tau varies between -1 and +1. It is negative when the trend decreases and positive when the trend increases. The Mann- Kendall test evaluates whether a series of random observations is consistent with presence of a trend. The null hypothesis is that the data do not exhibit a trend and the alternative hypothesis says the data exhibit a trend (Kulkarni, 1995).

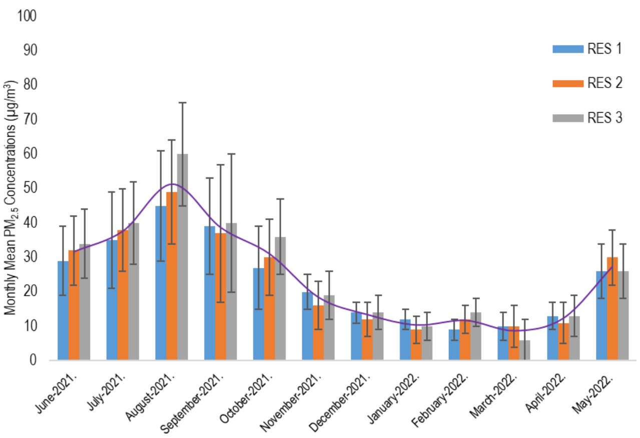

Figure 16: *10:00-12:00 hours monthly mean ambient $PM_{2.5}$ concentration for residential areas (bars indicate standard deviations).*

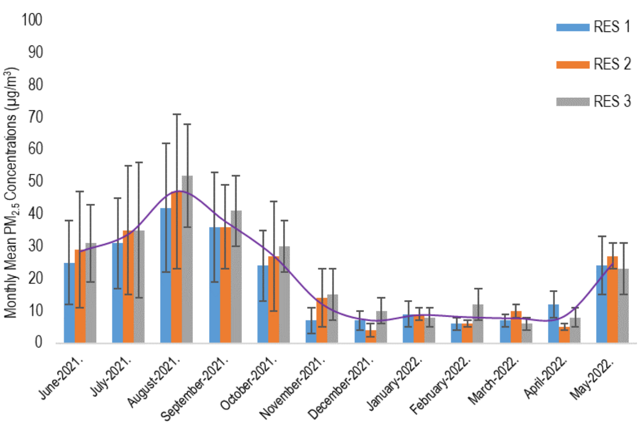

Figure 17: *15:00-17:00 hours monthly mean ambient $PM_{2.5}$ concentration for residential areas (bars indicate standard deviations).*

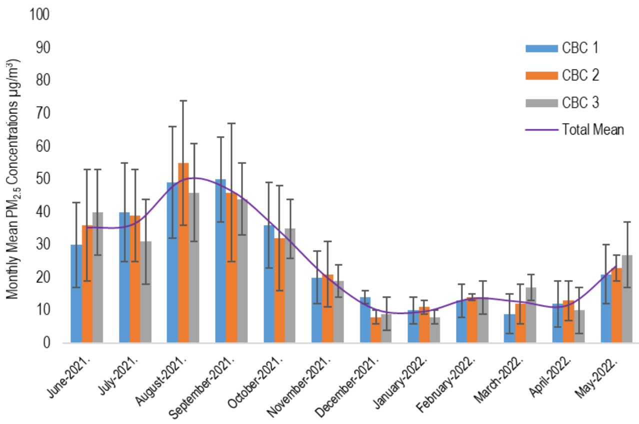

Figure 18: *10:00-12:00 hours monthly mean ambient $PM_{2.5}$ concentration for CBC (bars indicate standard deviations).*

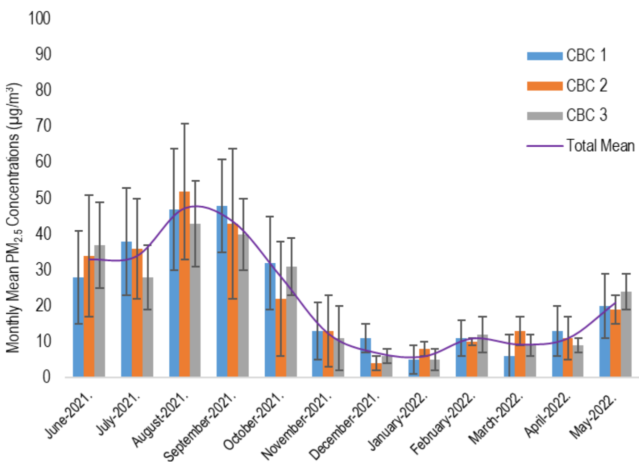

Figure 19: *15:00-17:00 hours monthly mean ambient $PM_{2.5}$ concentration for commercial and CBC (bars indicate standard deviations).*

Table 1: *Mann Kendall Trend test for June 2021 to September 2021, September 2021 to December 2021, and December 2021 to May 2022 in all the locations.*

		10:00-12:00		15:00-17:00	
Site	**Period**	**tau**	***p*-value**	**tau**	***p*-value**
School	June 2021-September 2021	1.000	0.089	0.667	0.308
	September 2021-December 2021	-1.000	0.027*	-0.800	0.086
	December 2021-May 2022	0.950	0.043*	0.949	0.043*
Hospital	June 2021-September 2021	0.330	0.734	<0.001	0.999
	September 2021-December 2021	0.800	0.086	-0.738	0.129
	December 2021-May 2022	0.527	0.312	0.527	0.312
Industry	June 2021-September 2021	1.000	0.089	1.000	0.089
	September 2021-December 2021	-1.000	0.027*	-1.000	0.027*
	December 2021-May 2022	0.800	0.086	0.949	0.043*
Market	June 2021-September 2021	0.667	0.308	0.667	0.308
	September 2021-December 2021	-1.000	0.027	-0.800	0.086
	December 2021-May 2022	0.200	0.807	<0.001	0.999
Residential	June 2021-September 2021	0.667	0.308	0.667	0.308
	September 2021-December 2021	-1.000	0.027*	-0.800	0.086
	December 2021-May 2022	0.527	0.312	0.120	0.999
CBC	June 2021-September 2021	0.667	0.308	0.667	0.308
	September 2021-December 2021	-0.949	0.043*	-1.000	0.027*
	December 2021-May 2022	0.400	0.462	0.738	0.129

*the p-value is less than 0.05 implying a significant trend in $PM_{2.5}$

In school campuses the $PM_{2.5}$ levels had a significant decreasing trend from September 2021 to December 2021 based on the measurements taken between 10:00 to 12:00 (tau = -1, p-value = 0.027, Table 1) and a no significant trend for the $PM_{2.5}$ levels obtained between 15:00 to 17:00 (tau = -1, p-value = 0.027, Table 1). However, the $PM_{2.5}$ levels were increasing significantly from December 2021 to May 2022 for both morning and evening measurements (Table 1). The $PM_{2.5}$ levels had a significant decreasing trend from September 2021 to December 2022 for both scheduled times for measurements (tau = -1, p-value = 0.027) while an increasing trend was observed between 15:00 to 17:00 during the same period (tau = 0.8, p-value = 0.043, Table 1).

In residential areas, the trend of $PM_{2.5}$ decreased significantly between September and December 2021 (tau = -1, p-value = 0.027, Table 1) whereas trends for June to September 2021 and December to May 2021 were not significant (p-value >0.05, Table 1). For CBC the trend of $PM_{2.5}$ levels were significantly decreasing between September and December 2021 (tau = 0.949, p-value = 0.027, Table 1) whereas no significant trend was observed from June to September 2021 and December to May 2022.

Conclusion

This study aimed at assessing the concentration changes of $PM_{2.5}$ in 18 sites at school campuses, hospitals, industrial areas, markets, residential areas and Blantyre CBC across Blantyre City, between 10:00-12:00 and 15:00-17:00. Climatology, vegetation, topography, domestic combustion of solid fuel and land clearing events across Blantyre may be associated with significant effects on ambient $PM_{2.5}$ concentrations. The yearly mean showed that high values of $PM_{2.5}$ concentrations was observed in industrial sites (62 ± 38 μg/m^3) followed by Market areas (44 ± 26 μg/m^3) for the 10:00-12:00 time period. The results showed a monthly diurnal variability, suggesting that rainfall season has a significant effect on $PM_{2.5}$ concentrations across Blantyre. Higher $PM_{2.5}$ concentrations were observed between the months of May and October, which are drier and windy months in Blantyre. Significant trends were observed for $PM_{2.5}$ levels in school campuses, industries, residential areas, and CBC while markets and hospitals did not show any significant trend. Since the $PM_{2.5}$ concentrations are high in Blantyre, it is important that people minimise the duration of stay in highly polluted areas and wearing of personal protective equipment like masks should be encouraged as well. Also, the local assembly should put in place measurers to improve air quality within the city. Although $PM_{2.5}$ concentration levels were lower between December and April, it is important to note that this was a characteristic of one year. Therefore, it is proposed that a long-term monitoring of $PM_{2.5}$ levels be done in Blantyre. A study of $PM_{2.5}$ concentrations source apportionment should also be done.

Conflict of interest

The authors declare no conflict of interest regarding the publication of this paper.

Data availability

The monitoring data used in this study are available upon request. Interested researchers can contact the corresponding author to obtain access to these data.

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Supplementary material

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