SPATIO-TEMPORAL VARIABILITY OF AIR QUALITY AND RELATIONSHIP WITH METEOROLOGICAL PARAMETERS IN CAPE TOWN, SOUTH AFRICA

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ABSTRACT:

African cities are growing fast, and this rapid urbanisation has tremendously increased air pollution and greenhouse gas emissions. Despite this disturbing reality, the deleterious impacts of air pollution on livelihoods and the environment are often overlooked. Recently, the link between air quality and meteorological parameters has received attention from researchers and understanding this relationship could significantly improve our understanding of the spatial and temporal dynamics of air quality. This study focuses on analysing the spatiotemporal variation of three key air quality parameters, namely nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and particulate matter (PM_{10}), in Cape Town between 2020 and 2021. The study also aims to assess the relationship between air quality and meteorological parameters during this period, and the compliance with national and international air quality guidelines. Air quality data were collected from five monitoring stations in the City of Cape Town. A preliminary analysis of the data reveals high increases in the concentration of air pollutants from 2020 to 2021. For instance, the average monthly concentration of NO_2 and SO_2 at Bellville South station more than doubled during this period (from 6.7 – 14.8 $\mu g/m^3$ and 3.4 – 8.1 $\mu g/m^3$, respectively). This is worrisome as the air quality index (AQI) exceeded the safe limits at several sites. There is a need for urgent action by national and city governments in Africa to invest in air quality monitoring systems to enhance the well-being of citizens and promote the long-term sustainability of cities and infrastructure.

1. INTRODUCTION

1.1 Background

Air pollution is a critical environmental issue that poses significant threats to human health and ecosystems (Shaddick et al., 2020; WHO, 2016). The detrimental impacts of air pollution have been extensively studied worldwide, prompting further investigations to enhance our understanding of its spatio-temporal variability and the underlying factors influencing it (Ramsey et al., 2014). This study focuses on the spatiotemporal variability of air quality and its relationship with meteorological parameters in Cape Town, South Africa. While previous research has explored the link between air quality and meteorological parameters (Xu et al., 2017; Zhao et al., 2018; Qiao et al., 2019), there is still a gap in our understanding of the specific dynamics in the context of Cape Town. Furthermore, the knowledge of the spatio-temporal variability of air pollutants and their association with meteorological parameters in Africa is still limited. Therefore, our research aims to fill this gap by investigating the air quality parameters, namely nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and particulate matter (PM_{10}), and their relationship with meteorological parameters in Cape Town.

To achieve this, we employ air quality data collected from air quality monitoring stations via the Cape Town open data portal - https://odp-cctegis.opendata.arcgis.com/. By analysing the data from 2020 to 2021, we evaluate the spatio-temporal patterns of air pollutants and identify any correlations with meteorological parameters.

This study will contribute new knowledge by providing an understanding of the spatio-temporal variability of air quality in Cape Town and its association with meteorological parameters. By conducting a detailed analysis, we aim to identify trends, or patterns in the air pollutant concentrations and their relationship with the meteorological parameters. Additionally, the pollutant concentrations are evaluated using national and international air quality index (AQI) guidelines. The findings of this study will have practical implications for policymakers and city governments in Cape Town and other African cities experiencing rapid urbanisation. Understanding air pollution dynamics and its relationship with meteorological parameters is crucial for implementing effective air quality management strategies and sustainable urban development plans.

We also discuss the implications of these findings for air quality management and provide recommendations for future research.

1.2 Study Area

Cape Town, often referred to as the Mother City, is one of South Africa's capital cities, serving as the legislative capital. Situated on the south-western coast, Cape Town is the largest city in the Western Cape region and is nestled beneath the awe-inspiring Table Mountain. Air quality is a significant concern in Cape Town as the city grapples with the challenge of maintaining clean and healthy air for its residents and the environment. Vehicular emissions are a primary contributor to

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air pollution in the city (Odhiambo et al., 2021; Tozer, 2020). With a growing population and increased reliance on cars, the city experiences elevated levels of pollutants such as nitrogen oxides (NOx) and particulate matter (PM). These pollutants can severely affect human health, including respiratory, cardiovascular, and other ailments (Manisalidis et al., 2020).

Industrial activities contribute to air pollution in Cape Town. The city hosts a range of industries, including manufacturing, refineries, and power generation, which release pollutants such as sulphur dioxide (SO_2), volatile organic compounds (VOCs), and particulate matter into the air. These emissions can contribute to smog formation and pose health risks to workers within the industries and nearby communities.

Furthermore, the unique topography of Cape Town can exacerbate air pollution issues. The city is surrounded by mountains, creating a bowl-like effect that traps pollutants and hampers their dispersal. This phenomenon, known as a temperature inversion, can lead to the accumulation of pollutants and the formation of localised pollution hotspots. Thus, understanding air pollution dynamics in Cape Town is crucial for developing effective strategies and policies to improve air quality and safeguard its residents' health and well-being. By understanding the sources, dynamics, and impacts of air pollution in the city, policymakers and relevant stakeholders can devise targeted interventions to mitigate pollution levels and create a healthier environment. Figure 1 shows the selected air quality monitoring stations in Cape Town.

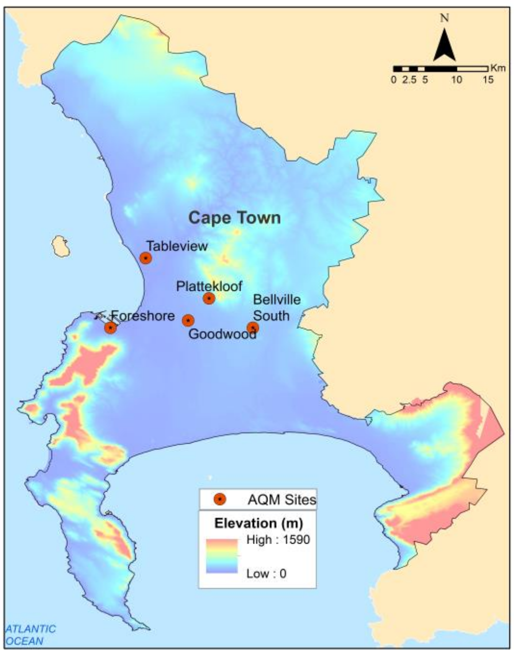

Figure 1. Selected air quality monitoring stations in Cape Town

2. METHODOLOGY

The workflow diagram of the methodology is shown in Figure 2.

2.1 Data Acquisition

Data on air quality parameters (SO_2, NO_2 and PM10) were acquired from the City of Cape Town Open Data Portal (https://odp-cctegis.opendata.arcgis.com/). The data collection is done at hourly intervals at several stations spread across the city. The five stations selected for this study are shown in Figure 1. Data on climatic/meteorological parameters were acquired from two sources: (i) rainfall data was acquired from the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) - https://chrsdata.eng.uci.edu/. The PERSIANN system was developed by the Centre for Hydrometeorology and Remote Sensing (CHRS), University of California. (ii) data on surface pressure, earth skin temperature, temperature at 2m, relative humidity at 2m, and wind speed at 50m were acquired from the Prediction of Worldwide Energy Resource (POWER) Project - https://power.larc.nasa.gov/data-access-viewer/. POWER is a National Aeronautics and Space Administration (NASA) Applied Sciences Program. The meteorological parameters are listed below:

Meteorological parameters:
Rainfall (mm)
PS MERRA-2 Surface Pressure (kPa)
TS MERRA-2 Earth Skin Temperature (C)
T2M MERRA-2 Temperature at 2 Meters (C)
RH2M MERRA-2 Relative Humidity at 2 Meters (%)
WS50M MERRA-2 Wind Speed at 50 Meters (m/s)

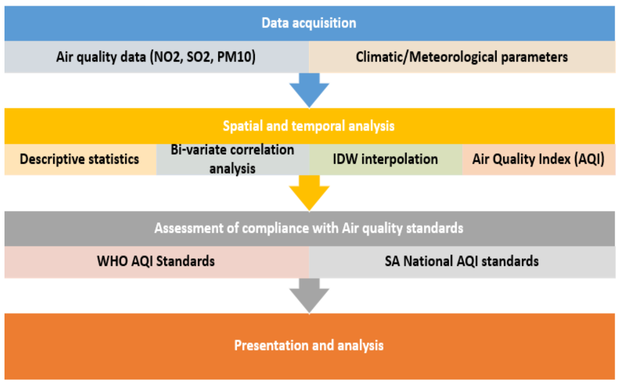

Figure 2. Workflow diagram of the methodology

2.2 Quantitative Analysis

The air quality and meteorological data were summarised using descriptive statistics. Additionally, correlation analysis was carried out to investigate the relationship between meteorological parameters and air pollutants. This analysis aimed to assess the potential impact of meteorological variables on air pollutants within the study area. The correlation coefficient or index was used to quantify the degree of the linear relationship between meteorological variables and air pollutants. This index ranges from -1 to +1, where a coefficient closer to +1 indicates a stronger relationship, while a coefficient closer to -1 suggests a weaker correlation. A coefficient of 0 indicates no relationship between the variables, while a coefficient of -1 or +1 signifies a complete negative or positive correlation, respectively.

We employed Pearson's correlation coefficient to conduct the correlation analysis, which aligns with the approach used in previous studies such as Tang et al. (2020) and Balogun and Tella (2022). By applying this method, we aimed to gain insights into the relationship between meteorological variables and air pollutants in the study area.

2.3 Spatial Interpolation

Inverse Distance Weighting (IDW) interpolation was used to estimate values at unsampled locations based on nearby sampled points. In the context of air quality, IDW interpolation can estimate the mean concentrations of SO_2, NO_2 and PM_{10} at locations where direct measurements are unavailable.

2.4 Compliance with AQI Standards

The compliance of the air quality in Cape Town to international and national air quality index (AQI) guidelines was assessed by comparing with the World Health Organization (WHO) air quality guidelines (AQGs) and estimated reference levels (RLs) (https://www.eea.europa.eu/publications/status-of-air-quality-in-Europe-2022/europes-air-quality-status-2022/world-health-organization-who-air), and the South Africa National ambient air quality standards (https://www.gov.za/documents/national-environmental-management-air-quality-act-national-ambient-air-quality-standards). Summarily, both guidelines specify the following AQIs as a safe limit:

WHO AQI standards (1 year average):

- SO_2: 40 ug/m^3
- NO_2: 10 ug/m^3
- PM_{10}: 15 ug/m^3

South Africa AQI standards (1 year average):

- SO_2: 50 ug/m^3
- NO_2: 40 ug/m^3
- PM_{10}: 40 ug/m^3

3. RESULTS AND DISCUSSION

3.1 Spatial and Temporal Variation of Air Quality Parameters

Figure 3 illustrates the progressive increase in concentrations of air pollutants across all stations from 2020 to 2021. In 2020, the mean annual concentration of SO_2 ranged from 3.39 to 4.11 µg/m³, while in 2021, it ranged from 1.89 to 8.12 µg/m³. The mean annual concentration of NO_2 ranged from 4.47 to 13.80 µg/m³ in 2020 and from 5.67 to 27.09 µg/m³ in 2021. Likewise, the mean annual concentration of PM_{10} ranged from 14.89 to 28.96 µg/m³ in 2020 and from 17.44 to 32.68 µg/m³ in 2021.

Among the studied air quality parameters, PM_{10} exhibited the highest concentrations between 2020 and 2021. This increase can possibly be attributed to the strict COVID-19 lockdown measures in 2020, which gradually eased in 2021. As the lockdown restrictions were lifted, economic activities, including industrial operations, transportation, and construction, likely resumed. Consequently, these activities might have led to increased emissions and higher concentrations of air pollutants. During the COVID-19 lockdown, transportation, particularly road traffic, significantly decreased. However, with the gradual release of the lockdown, commuting likely increased, resulting in higher vehicle emissions and elevated levels of nitrogen oxides and particulate matter. Furthermore, the reduced commercial and industrial activities during the lockdown period led to a decrease in energy consumption. As the lockdown eased, energy demand likely rose, leading to increased power generation, industrial operations, and associated emissions.

Bellville and Foreshore areas exhibited high concentrations of nitrogen dioxide and particulate matter, potentially indicating localized pollution sources or specific atmospheric conditions influenced by factors such as traffic congestion, industrial activities, topography, meteorological conditions, construction, and demolition. Particulate matter can originate from various sources, including natural sources like dust and sea salt, as well as human activities such as industrial processes, vehicle emissions, construction sites, and the combustion of fossil fuels. These particles can have adverse effects on human health and well-being.

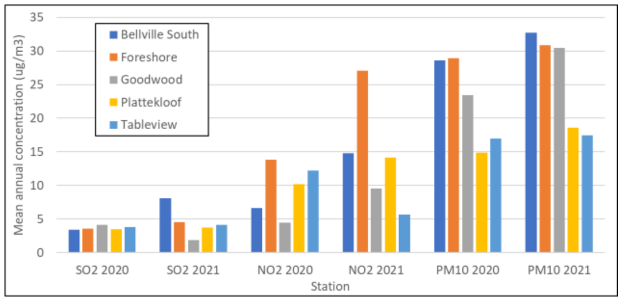

Figure 3. The trend of air pollutant concentrations in Cape Town, 2020 – 2021

Figure 4 shows the spatial distribution of air pollutant concentrations across the five monitoring stations.

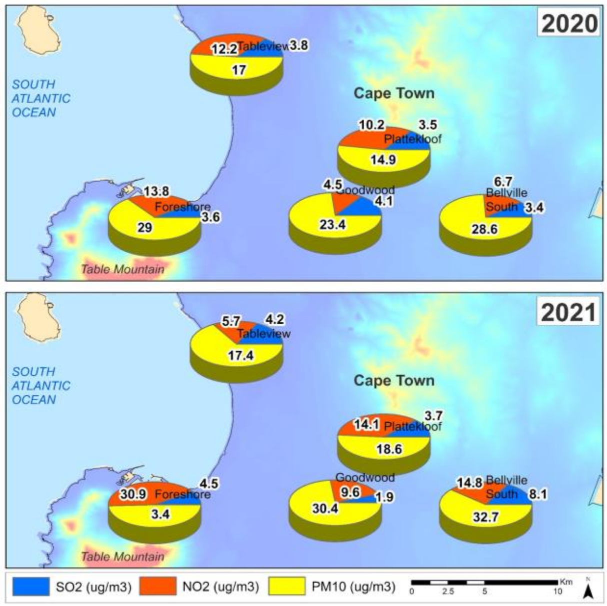

Figure 4. Spatial distribution of air pollutant concentrations across the five monitoring stations

Figure 5 depicts the IDW interpolation of mean SO_2 and NO_2, while Figure 6 demonstrates the IDW interpolation of PM_{10} and mean rainfall between 2020 and 2021 respectively. The results reveal areas with high concentrations of SO_2 and PM_{10} in specific regions of Cape Town, such as Bellville.

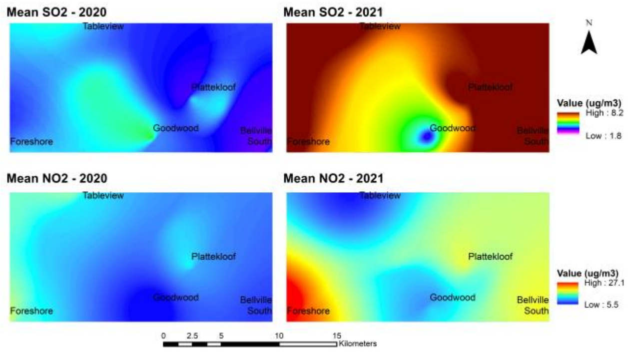

Figure 5. IDW interpolation of mean SO_2 and mean NO_2

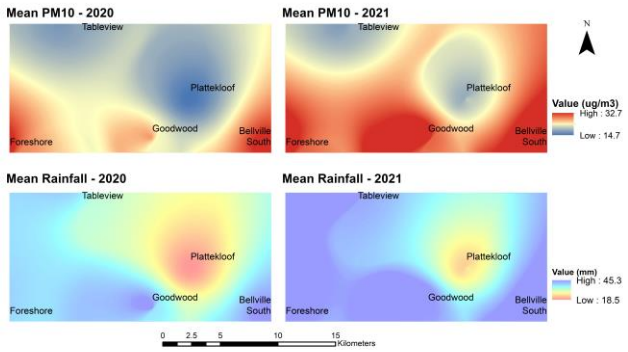

Figure 6. IDW interpolation of mean PM_{10} and mean rainfall

3.2 Correlation between Air Quality and Meteorological Parameters

The correlation between air quality and meteorological parameters was examined for Bellville, Foreshore, Goodwood, Plattekloof, and Table View during the years 2020 and 2021.

For example, In 2021, at Bellville, there was a strong positive correlation (r = 0.86 to 0.87) between the concentrations of SO_2, NO_2, and PM_{10}. Additionally, a moderate positive correlation (r = 0.54 to 0.69) was observed between air pollutants and rainfall. All three pollutant concentrations were positively correlated with relative humidity and surface pressure (r = 0.46 to 0.72), but negatively correlated with wind speed (r = -0.35 to -0.72). The analysis also indicates a moderate negative correlation (r = -0.53 to -0.73) between pollutant concentrations and temperature. Figures 7 – 10 present correlation heatmaps at some selected stations, for both years.

These findings suggest that specific meteorological parameters, such as rainfall, relative humidity, surface pressure, wind speed, and temperature, exhibit varying degrees of influence on air pollutant concentrations in the studied areas. The observed correlations provide insights into the complex interactions between meteorology and air quality dynamics, aiding in our understanding of the factors impacting local air pollution levels.

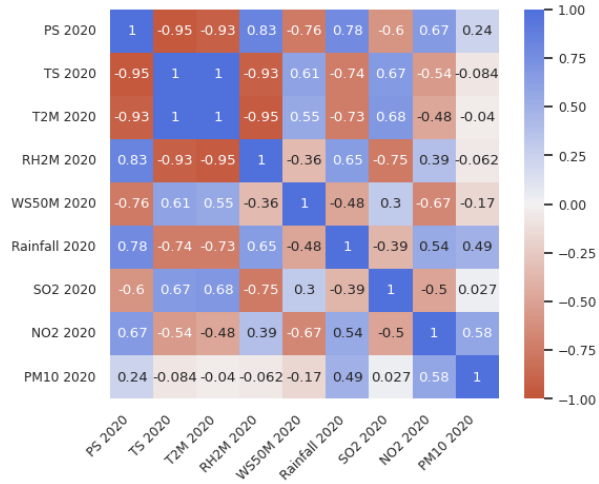

Figure 7. Heatmap showing correlation between air quality and meteorological parameters at Table View, 2020

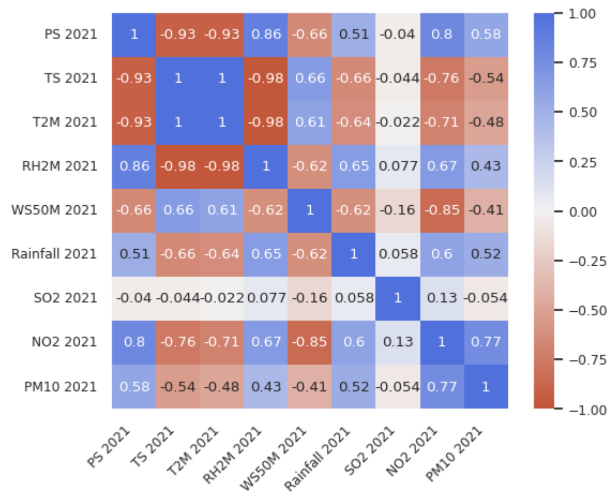

Figure 8. Heatmap showing correlation between air quality and meteorological parameters at Table View, 2021

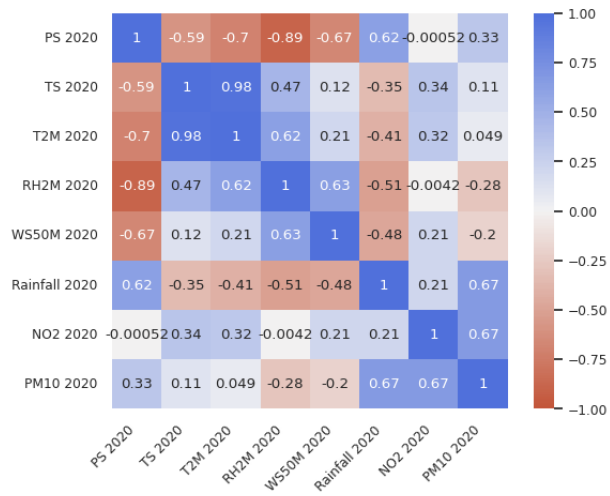

Figure 9. Heatmap showing correlation between air quality and meteorological parameters at Plattekloof, 2020

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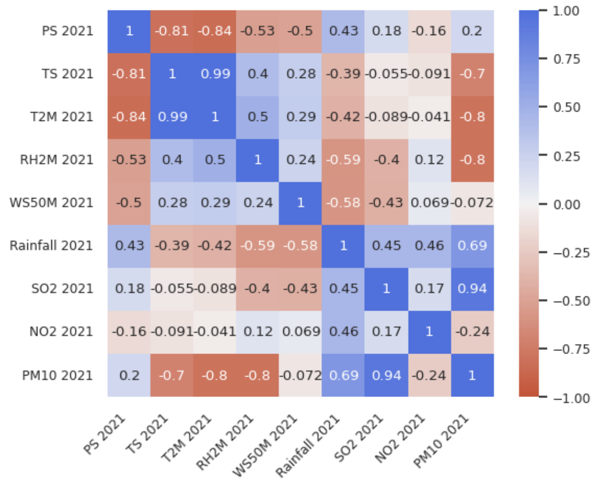

Figure 10. Heatmap showing correlation between air quality and meteorological parameters at Plattekloof, 2021

3.3 Comparison with AQI Standards

Figures 11 - 13 show the calculated AQIs for Cape Town based on WHO and South African AQI standards. Summarily, the AQI for SO_2 is generally below the safe limits of 40 ug/m^3 (WHO) and 50 ug/m^3 (South Africa) respectively between 2020 and 2021. Generally, the concentration levels of NO_2 at most stations exceed the safe limits of 10 ug/m^3 (WHO). However, in some stations, the concentration levels of NO_2 are below the safe limit of 40 ug/m^3 (South Africa). For PM, the calculated AQIs are generally higher or very close to the limits. The South African specified AQI limits are generally higher than the WHO specified limits. Thus, while some parts of Cape Town are found to exceed the WHO AQI limits, the same areas are safely within the limits defined by the South African standards.

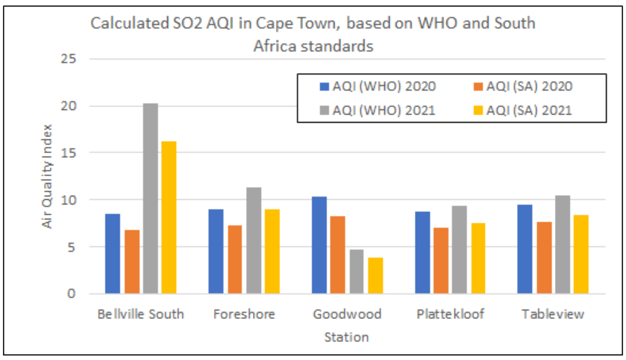

Figure 11. Comparison of the calculated SO_2 AQI based on WHO and South African AQI standards

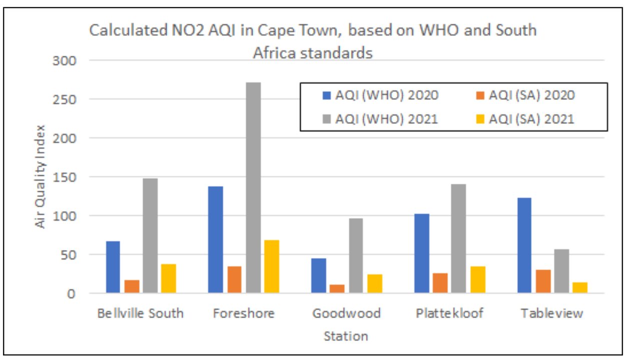

Figure 12. Comparison of the calculated NO_2 AQI based on WHO and South African AQI standards

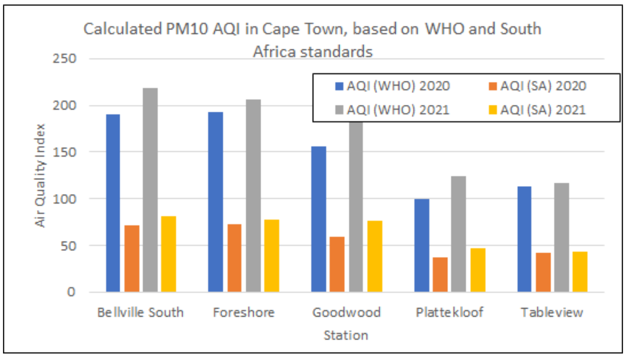

Figure 13. Comparison of the calculated PM_{10} AQI based on WHO and South African AQI standards

4. CONCLUSION

The study reveals an increase in nitrogen dioxide, sulphur dioxide, and particulate matter concentrations in neighbourhoods of Cape Town such as Bellville and Foreshore. The correlation between air quality and rainfall distribution underscores the intricate relationship between climate and air pollution. The escalating levels of pollutants pose significant health risks, including respiratory and cardiovascular ailments, necessitating prompt action. To ensure the long-term sustainability of cities and infrastructure, it is imperative to implement sustainable urbanization strategies and interventions.

To address the alarming air pollution levels in Bellville, Foreshore and other areas, detailed air quality monitoring and analysis specific to these areas should be conducted. This investigation will help identify the precise sources and factors contributing to the elevated concentrations of nitrogen oxides and particulate matter. Based on the findings, targeted measures can be implemented to reduce pollution levels, such as implementing stricter emission controls, improving urban planning, and enhancing public transportation options.

This study underscores the urgent need for comprehensive air quality management strategies and emphasizes the importance of mitigating the adverse effects of air pollution on human health and the environment. We can strive towards cleaner and healthier urban environments by adopting sustainable practices and implementing targeted interventions.

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