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LONG-TERM HEALTH RISK ASSESSMENT AND ENVIRONMENTAL BURDEN OF DISEASE OF CRITERIA AIR POLLUTANTS AMONG ADULTS IN MPUMALANGA HIGHVELD PRIORITY AREA, SOUTH AFRICA

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Abstract: The Mpumalanga Highveld Priority Area has been characterized by elevated concentrations of criteria air pollutants ($PM_{2.5}$, PM_{10}, SO_2, and NO_2). These criteria air pollutants have been globally associated with cardiopulmonary disease-related mortality. The primary objective of this study was to evaluate the human health risks and environmental burdens associated with inhalation exposure to $PM_{2.5}$, PM_{10}, SO_2, and NO_2 among adults in the Mpumalanga Highveld priority area. Hourly concentrations of $PM_{2.5}$, PM_{10}, SO_2, and NO_2 from monitoring stations in the Mpumalanga Highveld from January 1, 2009, to December 31, 2018, were obtained from the South African Air Quality Information System (SAAQIS) website. Daily cardiopulmonary disease-related mortality data for the same period were obtained from Statistics South Africa (Stats SA). The human health risk assessment framework, from hazard identification through dose-response assessment and exposure assessment to risk characterization, was applied to assess whether adults in the Mpumalanga Highveld priority area were exposed to $PM_{2.5}$, PM_{10}, SO_2, and NO_2 concentrations that may pose a non-carcinogenic health risk. The World Health Organization (WHO) guideline and relative risk were used to estimate the daily air quality health index (AQHI). Additionally, the environmental burden of disease resulting from exposure to $PM_{2.5}$ concentrations was evaluated. In the Mpumalanga Highveld, particulate matter (PM_{10} and $PM_{2.5}$) exceeded the annual National Ambient Air Quality Standards (NAAQS) of 20 $\mu g.m^{-3}$ and 40 $\mu g.m^{-3}$, respectively, for seven out of ten years in the Gert Sibande district and for eight out of ten years in the Nkangala district. The health risk assessment has shown that adults exposed to particulate matter may face non-carcinogenic risks, with a hazard quotient greater than 1. Furthermore, residents in the Gert Sibande district were exposed to healthy ambient air on only 21.73% of the days, moderate ambient air on 38.61%, and unhealthy ambient air on 40.23%. From 2008 to 2009, there were 23,383 and 31,349 cardiopulmonary disease-related mortality cases in the Gert Sibande and Nkangala districts, respectively. The attributable fraction indicates that 4.29% (1,003 deaths from cardiopulmonary diseases) could have been avoided if $PM_{2.5}$ had been below the annual South African National Ambient Air Quality Standard (SANAAQS) limit in the Gert Sibande district. Moreover, 20.56% (4,807 deaths from cardiopulmonary diseases) could

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have been avoided if $PM_{2.5}$ had been below the annual WHO guideline in the same area. The paper recommends that the South African Department of Environmental Affairs should review the SANAAQS.

Keywords: criteria air pollutants, health risk assessment, environmental burden of disease, cardiopulmonary disease-related mortality, air quality health index

1. Introduction

Air pollution problems are becoming more apparent, threatening human production, life, and sustainable social development (Mao et al., 2021). This is because air pollution introduces harmful substances (pollutants) in the form of particulate matter (PM2.5 and PM10), and gases (ground-level ozone, carbon dioxide, nitrogen oxides, and sulphur dioxide) (Abirami and Chitra, 2021). These pollutants severely impact the environment, human health, and the social economy (Bai et al., 2019). Exposure to these air pollutants has acute and chronic effects on human health, affecting several systems and organs (Abirami and Chitra, 2021). The effects range from minor upper respiratory irritation to chronic respiratory and heart disease, lung cancer, acute respiratory infection, and asthmatic attacks. At the same time, long-term exposure has also been linked with premature mortality and reduced life expectancy (Xie et al., 2017).

The adverse health impacts of air pollution have drawn worldwide attention for many decades (Huang et al., 2021). Particulate matter, SO2, NO2, CO and O3 has been declared major priority pollutants globally (Morakinyo et al., 2020). The World Health Organization (WHO) published global ambient air quality guidelines covering all six primary criteria pollutants in 2006 (WHO, 2006). The guidelines identify safe air quality levels for public health based on the extensive scientific evidence currently available and help governments set legally binding air quality standards. These guidelines were further updated in 2021, further tightening the recommended limits based on the latest evidence (WHO, 2021). In South Africa, the National Ambient Air Quality Standards (NAAQS) were established under the National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004), Section 9(1) (RSA, 2005). South Africa’s first legally binding NAAQS was promulgated in 2009 (DEA, 2009). The South African NAAQS provided two sets of standards: the less strict standards that were to be complied with immediately until 31 December 2014, and the strict standards that were to take effect on the 1st of January 2015. Notably, the PM2.5 was not included in the initial 2009 NAAQS. Following a statutory five-year review and growing recognition of PM2.5’s health impacts, South Africa established a national PM2.5 ambient standard in 2012 (DEA, 2012). The introduction of these standards marked a significant policy shift toward health-based air quality management in the country (Wright et al., 2012).

The human health risk assessment framework by the United States Environmental Protection Agency (USEPA) has been used globally in many studies (Amoatey et al., 2018; Heydari et al., 2019; Kim et al., 2018; Morakinyo et al., 2020, 2017; Odekanle et al., 2020) to estimate the health effects of exposure to air pollution concentrations above the NAAQS and WHO guideline. A study by Alfeus et al. (2024) conducted a health risk assessment of PM2.5 and associated trace elements in Cape Town, South Africa, and the hazard quotient (HQ) increased four times when using the WHO guideline compared to the South African NAAQS. Notably, the HQ for adults was below 1 when using the South African NAAQS. Similar observations were recorded by Howlett-Downing et al. (2023) in Pretoria, South Africa, and

Edlund et al. (2021) in Thohoyandou, South Africa. Although the South African NAAQS provided two sets of NAAQSs, the South African NAAQS are very high compared to the WHO guidelines. Higher NAAQS are prone to underestimating the health risks associated with air pollution in South Africa. Studies by Morakinyo et al. (2020, 2017) assessed the health risks associated with exposure to PM10, SO2, NO2, CO, and O3 in Pretoria West, South Africa. The study by Morakinyo et al. (2020) observed no non-carcinogenic effects in infants (0-1 years), toddlers (2–5 years), and adults (19-75 years), and a non-carcinogenic effect only in children (6-12 years). The outcome could have differed if stricter WHO guidelines had been used instead of the more lenient SA NAAQS standards. More importantly, South Africa's priority areas lack epidemiological studies that report the health impacts of air pollution. Epidemiological studies (Gray, 2019; Myllyvirta, 2014; Simelane and Langerman, 2024) conducted in the Mpumalanga Highveld Priority Area (HPA) focus on the health impacts and the burden of diseases associated with coal-fired power stations. Furthermore, the health impact figures in the Mpumalanga HPA Air Quality Management Plan were cited from the study conducted in 2002 (RSA, 2011), with limited coverage of the whole Mpumalanga HPA. This study examines the non-cancer health risks associated with long-term exposure to PM, SO2, and NO2 concentrations in the Mpumalanga Highveld priority area. The study will further assess the environmental burden of disease resulting from exposure to fine particulate matter exceeding the annual NAAQS and WHO guidelines.

2. Materials and Methods

2.1 Study area

Mpumalanga HPA was declared a priority area in 2007 due to its elevated concentrations of air pollutants. The Priority covers two districts in the Mpumalanga province: Gert Sibande and Nkangala. The two districts operate 12 of the 17 coal-fired power stations in South Africa, generating electricity. Figure 1 shows the location of the Mpumalanga Highveld priority area in South Africa. The top left plot shows the location of Mpumalanga province in South Africa, the bottom left plot shows the location of the Gert Sibande and Nkangala districts in Mpumalanga province, and the top right plot shows the location of the monitoring stations and the power stations in the two districts (Figure 1).

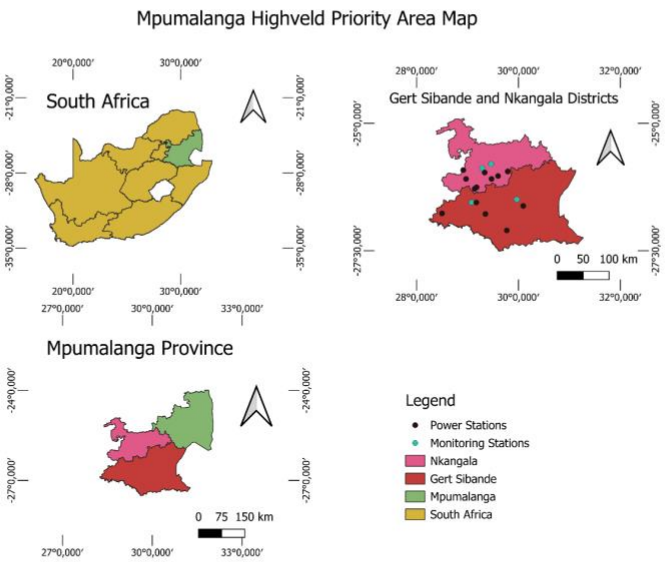

Figure 1: Mpumalanga Highveld Priority Area Map

2.2 Datasets

Hourly $PM_{2.5}$, PM_{10}, SO_2, and NO_2 concentrations were obtained from the SAAQIS website (https://saaqis.environment.gov.za/). The data were downloaded from four monitoring stations owned by the South African Weather Service, namely eMalahleni, Middelburg, Ermelo, and Secunda, from 01 January 2009 to 31 December 2018. Average concentrations between stations in the Gert Sibande district (Ermelo and Secunda monitoring stations) and the averages between the stations in the Nkangala district (eMalahleni and Middelburg monitoring stations) were calculated. The hourly averages were further aggregated to daily averages. The rationale was that the mortality data are given at the district level. The cardiopulmonary disease-related mortality data for the same period were requested from StatsSA for the Nkangala and Gert Sibande districts. The daily counts of cardiopulmonary disease for the population aged 30 years and above were calculated. The rationale for this was that the coefficient of the risk function for long-term exposure, recommended by the WHO for estimating the environmental burden of disease, was derived from a study on the impact of $PM_{2.5}$ exposure on cardiopulmonary disease-related mortality in populations above 30 years.

2.3 Health Risk Assessment

Health risk assessment is the process of assessing the health risk caused by environmental pollutants to the exposed population (Matooane and Diab, 2003). This study applied the same method to a study conducted in the Pretoria West industrial area (Morakinyo et al., 2020). The health risk assessment comprised four steps: Hazard identification, dose-response assessment, exposure assessment, and risk characterization

2.3.1 Hazard Identification

Hazard identification determines whether exposure to a pollutant can result in harmful health effects. This study utilized literature reviews to identify adverse health effects associated with exposure to $PM_{2.5}$, PM_{10}, SO_2, and NO_2.

2.3.2 Dose–response assessment

This step assesses the association between the dose and the outcome, considering the duration of exposure. In this study, we did not measure how adults react to exposure to criteria air pollutants; instead, we compared the measured concentrations of criteria air pollutants with the NAAQS and WHO guidelines.

2.3.3 Exposure assessment

Assess the population exposed and the magnitude and duration of exposure. In the absence of data related to the magnitude, frequency, and duration of exposure of the adult population in Mpumalanga Highveld, the default values based on the USEPA equations were used.

2.3.4 Risk characterization

Quantitative estimation of the health risk of exposure to a pollutant. This study used the hazard quotient (HQ) to estimate the probability of non-carcinogenic health effects due to inhaling PM, SO_2, and NO_2. The criteria air pollutants measured were used to show how exposure to criteria air pollutants above the NAAQS and WHO guideline can impact the likelihood and severity of health effects.

To calculate the Field Average Daily Dose (FADD), the average concentrations (C) of criteria pollutants monitored in the Mpumalanga highveld priority area were multiplied by the Inhalation Rate (IR), Exposure Frequency (EF), and Exposure Duration (ED) and then divided by the Body Weight (BW) multiplied by the Average Time (AT).

FADD was calculated using equation 1:

$$FADD_i = \frac{C_i \times IR \times EF \times ED}{BW \times AT} \quad (1)$$

Where: $FADD_i$ is the dose that the adult population of the Mpumalanga Highveld priority area may be exposed to when inhaling air with i^{th} criteria air pollutant concentrations measured at the Mpumalanga priority area from January 2009 to December 2018, expressed in $\mu g.kg^{-1}.day^{-1}$. C_i is the annual average value of the i^{th} criteria air pollutants concentration in the atmosphere expressed in $\mu g.m^{-3}$. IR is the amount of contaminated air inhaled per unit of time, expressed in $m^3.day^{-1}$. EF is the frequency of exposure of the adult population to i^{th} criteria air pollutant concentrations. ED is the duration of exposure to the i^{th} criteria air pollutant concentrations expressed in years. BW is the average body weight of the adult person over the exposure period (kg). AT is the period over which exposure is averaged.

Table 1: Health risk assessment input data for non-carcinogenic effects.

Parameters	Value	Reference
Inhalation Rate (IR)	15.9	(Alfeus et al., 2022)
Exposure Frequency (EF)	350	(Morakinyo et al., 2020)
Exposure Duration (ED)	30	(Morakinyo et al., 2020)
Body Weight (BW)	73.7	(Alfeus et al., 2022)
Average Time (AT)	10950	(Morakinyo et al., 2020)

The Safe Average Daily Dose (SADD) was calculated as follows:

$$SADD_i = \frac{C_i \times IR \times EF \times ED}{BW \times AT} \quad (2)$$

Where: $SADD_i$ is the dose that the population of Mpumalanga may be exposed to without suffering negative health risks, expressed in µg.kg^{-1}.day^{-1}. In this case, the concentration C_i represents the South African annual NAAQS and the WHO guideline for i^{th} criteria air pollutant expressed in µg.m^{-3}. The rest of the formula is the same as described above.

The risks caused by exposure to the i^{th} criteria air pollutants concentration is the potential risk to the onset of illness or exacerbations of disease in the exposed population in the Mpumalanga Highveld Priority Area population. The information developed in the previous three steps (hazard identification, exposure assessment, and dose-response assessment) was combined in the risk characterization step to quantify the potential health risks in the exposed population, expressed as an HQ.

The HQ was calculated using equation 3:

$$HQ_i = \frac{FADD_i}{SADD_i} \quad (3)$$

Where: HQ is the Hazard Quotient (which is always unitless), FADD is the Field Average Daily Dose, and SADD is the "safe" average daily dose of the i^{th} criteria air pollutants concentration. HQ below 1 indicates no hazard, and HQ above 1 indicates risk of non-carcinogenic effects.

2.4 Air quality health index (AQHI)

The methodology to estimate the AQHI is adopted from a study conducted by Adebayo-Ojo et al., (2023). The Methodology consists of five steps; the first step in developing AQHI is obtaining the concentration-response function (CRF). The second step is to derive the daily excess risk of death for each pollutant using the CRF. The third step involves scaling the pollutant's excess risk according to the WHO guidelines. The fourth step includes the calculation of the weighted average AQHI. The last step is categorizing ambient air quality based on the AQHI level. The same CRF from Adebayo-Ojo et al., (2023) were used in this study as well (Table 2). The ambient concentration reference value for each pollutant is based on the 2021 WHO long-term AQG values. Notably, the 2021 WHO AQG did not include a long-term value for SO_2; therefore, the study used the value from the 2000 WHO AQG.

The obtained CRF was used to calculate the excess risk using the equation below:

$$pollutant\ i\ excess\ risk\ on\ day\ t = 100\left(e^{\beta_i c_i} - 1\right) \quad (4)$$

$$\beta_i = coeffcient\ per\ 1\frac{ug}{m3}increase\ of\ pollutant\ i,\ c_i(t) = long - term\ WHO\ AQG\ concentration\ of\ pollutant\ i\,) \quad (5)$$

After obtaining the daily pollutants' excess risk, the study uses the same linear scale, ranging from 1 to 10+, to scale the pollutant excess risk. For each pollutant, the percent increase per unit of the index was chosen so that the index value of 3 corresponds to the ER at the WHO long-term reference values. The next step is to calculate the daily average AQHI, calculated as the weighted mean of the index values of the different pollutants using equation 6:

$$weighted\ average\ AQHI\ (t)\ = \frac{1}{\sum W_i} \sum_{i=1 \ldots n} W_i * AQHI_i\ (t) \qquad (6)$$

Where m = number of pollutants used in AQHI, I = pollutant, $AQHI_i\ (t)$ = derived index value for pollutant I on day t and W_i = weight of $AQHI_i\ (t)$

In the last step, the AQHI is categorized into colour schemes. Green (AQHI level 1 – 3) represents healthy ambient air, yellow (AQHI level 4 – 5) represents moderate ambient air, orange (AQHI level 6 – 7) represents unhealthy ambient air, red (AQHI level 8 – 9) represents unhealthy ambient air, and purple (AQHI level 10+) represents hazardous ambient air.

Table 2: Summary of values used in AQHI (Adebayo-Ojo et al., 2023).

Pollutant p	**CRF published in WHO AQG (per 10 µg.m^{-3})**	**Beta coefficient per 1 µg.m^{-3}**	**WHO AQG reference value in µg.m^{-3} for index value = 3**	**ER (%) at index value = 3**	**Average ER (%) per index unit**	**Inverse weight for PM_{10}-based AQHI**
$PM_{2.5}$	1.0065	0.00065	5	0.326	0.109	-
PM_{10}	1.0041	0.00041	15	0.617	0.206	1
NO_2	1.0072	0.00072	10	0.723	0.241	0.853
SO_2	1.0059	0.00059	20	1.187	0.396	0.519
O_3	1.0043	0.00043	60	2.614	0.871	0.236

2.5 Environmental burden of disease

Environmental Burden Disease (EBD) due to air pollution was carried out following similar studies (Amoatey et al., 2018; Chalvatzaki et al., 2019). The number of deaths caused by cardiopulmonary diseases due to long-term exposure to $PM_{2.5}$ is determined using log-linear models recommended by the WHO (Ostro, 2004). The EBD was calculated using relative risk (RR), which is an estimate of the likelihood of cardiopulmonary mortality in people exposed to $PM_{2.5}$ levels higher than the theoretical counterfactual concentration, and attributable fractions (AF), which estimate the percentage of deaths from cardiopulmonary disease that could be prevented if $PM_{2.5}$ levels were lowered to the theoretical counterfactual concentration (Odekanle et al., 2020). RR was calculated using equation 7:

$$RR = \left[\frac{X\ + 1}{X_O\ + 1}\right]^{\beta} \qquad (7)$$

The attributable fractions are given by equation 8:

$$AF = \frac{RR - 1}{RR} \quad (8)$$

X = mean concentration of the pollutants; X_O = baseline concentration: 20 μg.m^{-3} (NAAQS) and 5 μg.m^{-3} (WHO guideline); β = coefficient of risk function for long-term exposure, which is 0.15515 (95% CI: 0.0562,0.2541) for cardiopulmonary mortality (Ostro, 2004).

The data were analysed using RStudio V1.3.1093 software for Windows (Affero General Public License v). On March 14, 2021, the University of Venda Research Ethics Committee granted ethical clearance for this study (Reference number: 2021/03/007).

3. Results and Discussion

3.1 Criteria air pollutant concentrations

Table 3 Presents the descriptive statistics of the criteria air pollutants in the Gert Sibande district. The table shows the year, the criteria air pollutant with its annual mean plus/minus standard deviation, and the N days (the Number of days when the concentrations exceeded the 24-hour NAAQS). The 24-hour SANAAQS are 40 μg.m^{-3} for $PM_{2.5}$, 75 μg.m^{-3} for PM_{10}, and 48 ppb for SO_2. The Annual SANAAQS are 20 μg.m^{-3} for $PM_{2.5}$, 40 μg.m^{-3} for PM_{10}, 19 ppb for SO_2 and 21 ppb for NO_2. In 2009 average $PM_{2.5}$ was 34.72 ± 24.42 μg.m^{-3} with 104 days of 24-hour exceedances, PM_{10} average was 62.22 ± 43.76 μg.m^{-3} with 106 days of 24-hour exceedances, SO_2 average was 8.26 ± 3.81 ppb and NO_2 average was 18.85 ± 9.13 ppb (Table 3). Particulate matter continuously exceeded the annual NAAQS, except in 2015 and 2018. SO_2 never exceeded the annual NAAQS, and NO_2 concentrations exceeded the annual NAAQS once in 2017.

Table 3: Descriptive statistics of criteria air pollutants at Gert Sibande district

Year	$PM_{2.5}$		PM_{10}		SO_2	NO_2
	Mean ± SD	N days	Mean ± SD	N days	Mean ± SD	Mean ± SD
2009	34.72 ± 24.42	104	62.22 ± 43.76	106	8.26 ± 3.81	18.85 ± 9.13
2010	34.90 ± 24.04	116	70.24 ± 48.44	136	14.23 ± 6.29	15.51 ± 8.27
2011	28.70 ± 23.82	57	59.97 ± 42.92	83	14.99 ± 11.51	5.33 ± 2.07
2012	26.44 ± 18.46	61	56.89 ± 42.33	86	15.57 ± 9.94	9.06 ± 5.74
2013	26.61 ± 20.95	85	62.60 ± 49.77	127	12.87 ± 4.60	16.11 ± 9.69
2014	19.80 ± 16.27	47	41.94 ± 35.06	63	8.75 ± 4.94	13.65 ± 6.61
2015	14.26 ± 10.93	12	36.31 ± 28.23	44	7.39 ± 4.47	14.42 ± 10.29
2016	23.61 ± 18.61	74	52.40 ± 45.89	105	7.64 ± 4.81	12.40 ± 3.85
2017	30.40 ± 23.74	107	64.78 ± 49.14	115	7.32 ± 4.32	27.02 ± 18.67
2018	14.72 ± 6.91	1	29.67 ± 15.81	4	5.46 ± 3.46	15.46 ± 9.46

Table 4 presents the descriptive statistics of the criteria air pollutants in the Nkangala district. The table shows the year, the criteria air pollutant with annual mean plus/minus standard deviation, and the N days (the Number of days where the concentrations exceeded the 24-hour NAAQS). In 2009, the average $PM_{2.5}$ was 25.93 ± 18.14 $\mu g.m^{-3}$ with 69 days of 24-hour exceedances, the average PM_{10} was 44.51 ± 31.40 $\mu g.m^{-3}$ with 72 days of 24-hour exceedances, the average SO_2 was 14.21 ± 10.20 ppb with 2 days of 24-hour exceedances, and the average NO_2 was 22.33 ± 9.93 ppb.

$PM_{2.5}$ exceeded the annual NAAQS every year except in 2014 and 2016. PM_{10} did not exceed the annual NAAQS only in 2014, 2016, and 2017. SO_2 never exceeded the yearly NAAQS. However, on some days, daily SO_2 concentrations exceeded the 24-hour NAAQS. These days did not result in overall exceedance, as there are four allowed exceedances of 24-hour NAAQS per year. The number of days per year when daily SO_2 concentrations exceeded the 24-hour NAAQS ranged from 0 to 3. NO_2 exceeded the NAAQS once in 2009.

Table 4: Descriptive statistics of criteria air pollutants in Nkangala district

Year	**$PM_{2.5}$**		**PM_{10}**		**SO_2**		**NO_2**
	Mean ± SD	N days	Mean ± SD	N days	Mean ± SD	N days	Mean ± SD
2009	25.93 ± 18.14	69	44.51 ± 31.40	72	14.21 ± 10.20	2	22.33 ± 9.93
2010	25.49 ± 17.22	72	44.78 ± 30.44	65	12.46 ± 7.73	1	14.32 + 6.13
2011	26.56 ± 15.42	56	54.42 ± 33.20	77	13.90 ± 8.78	1	11.08 ± 5.02
2012	22.01 ± 14.69	40	52.79 ± 41.29	98	11.65 ± 7.96	0	9.44 ± 3.99
2013	20.92 ± 13.72	38	44.92 ± 29.18	61	13.24 ± 9.45	1	14.76 ± 5.95
2014	14.04 ± 9.67	6	26.84 ± 19.64	6	12.05 ± 9.09	3	11.60 ± 5.40
2015	21.10 ± 16.97	57	49.55 ± 41.25	88	10.87 ± 8.17	0	15.81 ± 8.07
2016	16.57 ± 10.48	14	37.32 ± 24.22	33	9.64 ± 7.69	0	13.75 ± 7.40
2017	28.49 ± 18.64	84	31.44 ± 19.51	11	9.96 ± 7.84	2	11.50 ± 6.36
2018	26.52 ± 13.64	61	47.83 ± 29.22	72	10.61 ± 6.96	1	14.85 ± 6.81

The results consistently show that particulate matter ($PM_{2.5}$ and PM_{10}) exceeded both the South African National Ambient Air Quality Standards (SANAAQS) and the more stringent WHO guidelines, with frequent exceedances across both Nkangala and Gert Sibande districts. The Gert Sibande district exceeded the PM_{10} and $PM_{2.5}$ NAAQS almost every year from 2009 to 2018. The annual average exceedances were observed in seven out of 10 years for $PM_{2.5}$ and eight out of 10 years for PM_{10}. The regulation only allows four exceedances per year. However, the number of exceedances where $PM_{2.5}$ concentrations exceeded the annual NAAQS ranged from 57 to 116 per year. The number of exceedances where PM_{10} concentrations exceeded the annual NAAQS ranged from 63 to 136 per year. That is 16 to 34 times the number of exceedances allowed per year. Although the particulate matter concentrations are decreasing, high particulate matter levels were observed in Gert Sibande compared to the Nkangala district. Similar observations were made by (Arowosegbe et al., 2021; Feig et al., 2019; Garland et al., 2017). High SO_2 concentrations were measured in the Nkangala districts, which could be attributed to the proximity of the monitoring stations to industrial activities, including coal-fired power stations, compared to the monitoring stations in the Gert Sibande districts. However, both districts comply with the SO_2 24-hour and annual NAAQS. NO_2 concentrations are increasing in both districts, which can be attributed to the rise in vehicle traffic on the roads (McDaid, 2014).

3.2 Human health risk assessment

Figure 2 illustrates the annual hazard quotient for each air pollutant criterion in the Gert Sibande district. The Y-axis shows the hazard quotient, and the X-axis shows the year. The bar graph illustrates $PM_{2.5}$ in light blue bars, PM_{10} in brown bars, SO_2 in grey bars, and NO_2 in dark blue bars, with the yellow horizontal line indicating the hazard quotient. The plot on the left shows the HQ when using the SA NAAQS as the reference value, and the plot on the right shows the HQ when using the WHO guideline as a reference value. The hazard quotients below one show that the criteria pollutants were below the NAAQS and WHO guideline. In contrast, a hazard quotient above one shows that the criteria air pollutants exceed the NAAQS and WHO guidelines, and therefore pose a non-carcinogenic risk to the adult population in the Gert Sibande district. Particulate matter posed a non-carcinogenic risk almost every year, except in 2015 and 2018. For the gaseous pollutants, only NO_2 posed a non-carcinogenic risk in 2017 when using the SA NAAQS. However, when using the WHO guideline as a reference, all criteria pollutants posed a high non-carcinogenic risk every year except for SO_2 in 2017.

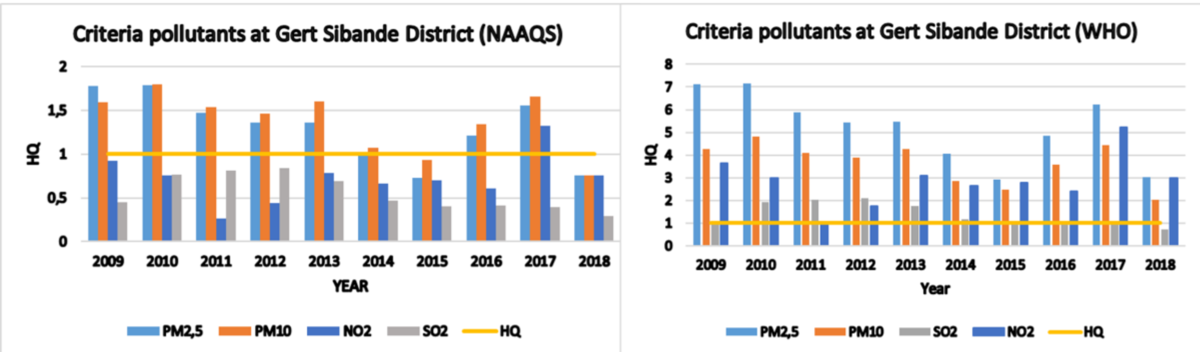

Figure 2: Health risk assessment of criteria air pollutants at Gert Sibande district

Figure 3 shows the hazard quotient for each criteria air pollution per year in the Nkangala district. The Y-axis shows the hazard quotient, and the X-axis shows the year. The bar graph illustrates $PM_{2.5}$ in light blue bars, PM_{10} in brown bars, SO_2 in grey bars, and NO_2 in dark blue bars, with the yellow horizontal line indicating the hazard quotient. The plot on the left shows the HQ when using the SA NAAQS as the reference value, and the plot on the right shows the HQ when using the WHO guideline as a reference value. Particulate matter continuously exceeded the NAAQS; thus, its hazard quotient is above most years except for 2014 and 2016. SO_2 average concentrations were below the annual NAAQS throughout the period, and therefore, the hazard quotient is below 1. However, when using the WHO guideline as a reference, all criteria pollutants posed a high non-carcinogenic risk every year

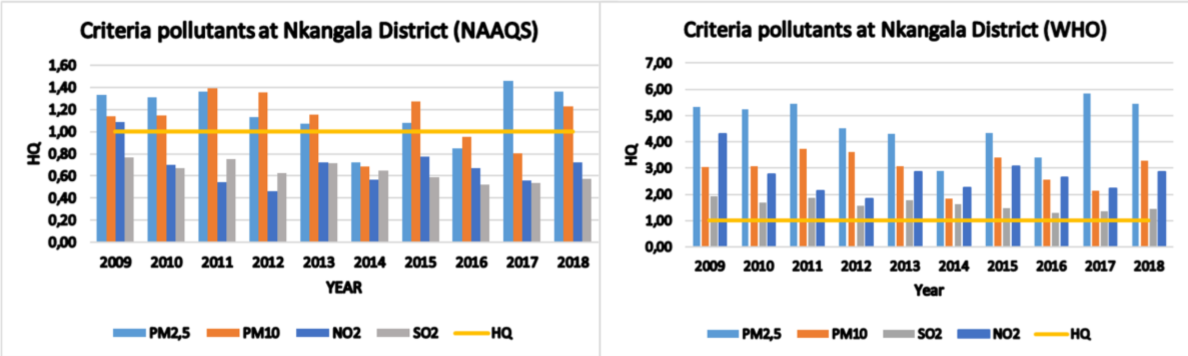

Figure 3: Health risk assessment of criteria air pollutants in Nkangala district

The hazard quotient analysis indicates that adults in these districts were at risk of non-carcinogenic effects nearly every year due to exposure to particulate matter above the NAAQS. When the WHO guidelines were used as a reference, the magnitude of the risk was found to be four times greater. This aligns with findings from other South African studies in Pretoria (Howlett-Downing et al., 2023), Cape Town (Alfeus et al., 2022), and Thohoyandou (Edlund et al., 2021), which showed that applying stricter WHO thresholds reveals a much higher public health risk than when using national standards. Notably, when using WHO guidelines, even gaseous pollutants NO_2 and SO_2 pose a non-carcinogenic risk, highlighting the inadequacy of the current South African standards.

3.3 Air quality health index

Table 5 presents the summary of the daily weighted air quality health index and the means of the criteria pollutants per AQHI level at the Gert Sibande district. The first column presents the AQHI level; the second column to the sixth column present the mean of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and O_3 for that AQHI level; the seventh column is the number of days and percentage for each AQHI level; the last column is the number of days and the percentage of days for that category of the air. The AQHI levels 1–3 represent healthy ambient air, 4–5 moderate ambient air, 6–7 unhealthy ambient air, 8–9 very unhealthy ambient air, and 10+ hazardous ambient air. From 2009 to 2018, the ambient air at Gert Sibande was only healthy on 21.73% of the days, moderate for 38.61%, and the remaining 40.23% of the days, the air was unhealthy.

Table 5: Summary of daily weighted air quality health index at Gert Sibande district

Weighted AQHI	$PM_{2.5}$	PM_{10}	SO_2	NO_2	O_3	N Days (%)	N Days (%)
1	2.82	4.24	3.88	4.08	28.51	13 (0.36%)	773 (21.17%)
2	5.73	9.45	6.35	6.82	27.08	247 (6.76%)	
3	9.52	17.02	7.17	8.79	27.31	513 (14.05%)	
4	14.44	27.31	8.14	11.23	26.97	607 (16.62%)	1410 (38.61%)
5	22.08	48.51	10.06	11.62	34.26	803 (21.99%)	

6	36.25	80.63	12.16	15.74	31.47	790 (21.63%)	1273 (34.86%)
7	43.36	91.09	13.38	25.13	29.6	483 (13.23%)	
8	53.02	111	15.37	35.55	30.05	195 (5.34%)	196 (5.37%)
9	76.61	132.92	43.07	64.1	21.16	1 (0.03%)	

Figure 4 presents the daily weighted air quality health index at the Gert Sibande district. The x-axis shows the months, and the y-axis shows the years. Each day is color-coded to correspond with its daily weighted AQHI. Days associated with unhealthy ambient air quality at Gert Sibande can be observed during winter.

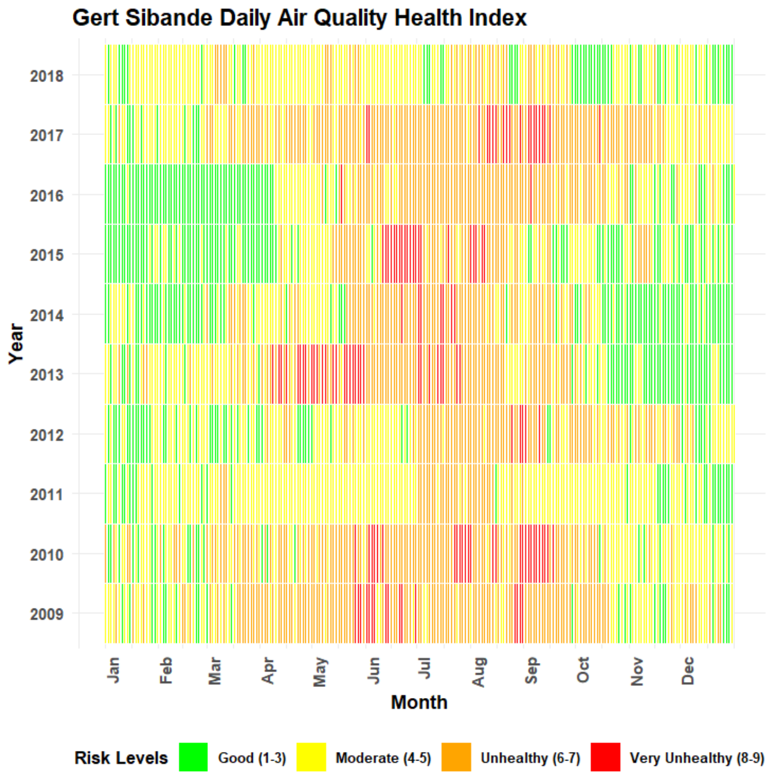

Figure 4: Daily weighted air quality index at Gert Sibande district

Table 6 presents the summary of the daily weighted air quality health index and the means of the criteria pollutants per AQHI level at the Nkangala district. The first column presents the AQHI level; the second column to the sixth column present the mean of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and O_3 for that AQHI level; the seventh column is the number of days and percentage for each AQHI level; the last column is the number of days and the percentage of days for that category of the air. From 2009 to 2018, residents in the Nkangala district were exposed to healthy ambient air for only 26.51% of the days, moderate ambient air for 34.17% of the days, and to unhealthy ambient air for the remaining 39.32% of the days.

Table 6: Summary of daily weighted air quality health index at Nkangala district

Weighted AQHI	$PM_{2.5}$	PM_{10}	SO_2	NO_2	O_3	N Days (%)	N Days (%)
1	3.47	5.01	3.43	3.71	20.09	11 (0.30%)	968 (26.51%)
2	8.7	9.5	5.8	6.63	28.66	254 (6.96%)	
3	13.06	16.84	7.28	8.67	29.34	703 (19.25%)	
4	15.11	25.39	9.65	11.47	26.12	661 (18.10%)	1248 (34.17%)
5	20.85	43.3	10.61	12.56	24.25	587 (16.07%)	
6	28.94	61.95	13.46	14.8	23.03	770 (21.08%)	1234 (33.79%)
7	37.29	77.19	17.9	22.12	19.21	464 (12.71%)	
8	48.1	91.41	24.9	31.73	18.08	184 (5.04%)	202 (5.53%)
9	57.49	99.43	45.82	35.9	13.84	18 (0.49%)	

Figure 5 presents the daily weighted air quality health index at the Nkangala district. The x-axis shows the months, and the y-axis shows the years. Each day is color-coded to correspond with its daily weighted AQHI. Days associated with unhealthy ambient air quality at Nkangala can be observed during winter. In contrast, days associated with healthy ambient air quality can be observed during summer.

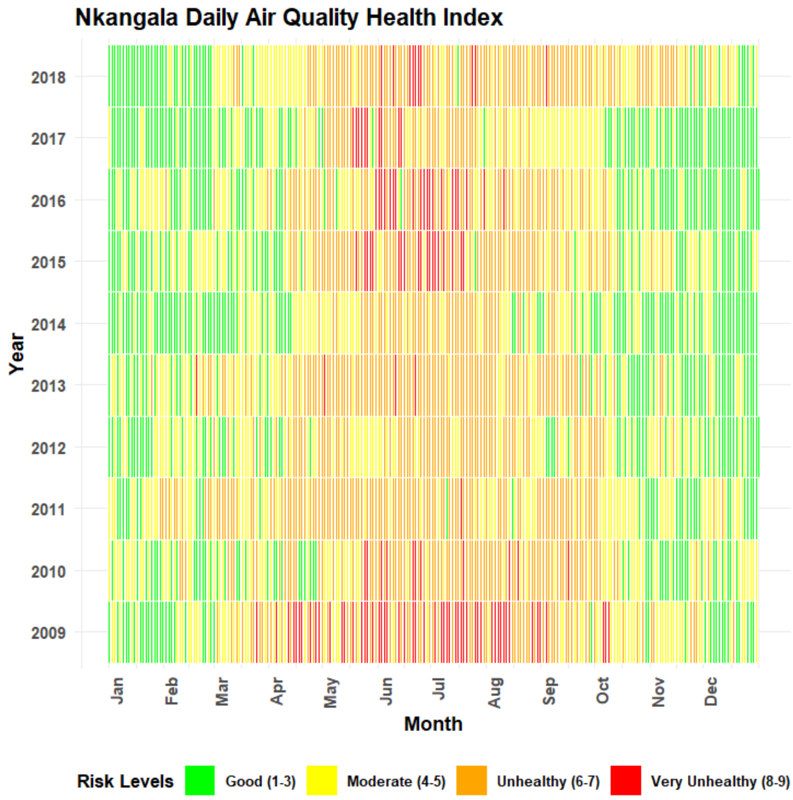

Figure 5: Daily weighted air quality index at Nkangala district

The Air Quality Health Index (AQHI) further reveals that residents in both districts were exposed to moderate to unhealthy air for 78.84% and 73.49% of the time at Gert Sibande and Nkangala districts, respectively. Highlighting the urgency to reduce air pollution emissions from all sources in the Mpumalanga Highveld Priority Area.

3.4 Environmental burden of disease

Table 7 presents the environmental disease burden associated with $PM_{2.5}$ exposure in the adult population of the Gert Sibande district. The first column shows the year, the second column indicates the number of death per year, the third column shows the percentage of attributable fraction (95% and confidence interval) of cardiopulmonary diseases related death and the fourth column indicates the number of death attributable to the exposure to $PM_{2.5}$ concentrations above the NAAQS in adults population in Nkangala district, the firth column shows the percentage of attributable fraction (95% and confidence interval) of cardiopulmonary diseases related death and the sixth column shows the number of death attributable to the exposure to $PM_{2.5}$ concentrations above the WHO guideline in adults population in Gert Sibande district. In 2009, we observed 3313 total deaths in the adult population due to cardiopulmonary disease. 7.9% of deaths were attributable to exposure to $PM_{2.5}$ above NAAQS, which is equivalent to 262 cardiopulmonary disease-related deaths in the adult population in the Gert Sibande district in 2009. Whereas 24.2% of deaths were attributable to exposure to $PM_{2.5}$ above the WHO guideline, which is equivalent to 801 cardiopulmonary disease-related deaths in the adult population in the Gert Sibande district in 2009. The (-) shows the years where $PM_{2.5}$ was below the NAAQS, for example, in 2015 and 2017. In total, there were 23383 cardiopulmonary disease-related deaths in the adult population in Gert Sibande. Of these, 1003 cardiopulmonary disease-related deaths were attributable to exposure to $PM_{2.5}$ above the NAAQS, and 4807 cardiopulmonary disease-related deaths were attributable to exposure to $PM_{2.5}$ above the WHO guidelines.

Table 7: Environmental burden of disease in the Gert Sibande district

		NAAQS		**WHO Guideline**	
Year	N death	AF [95% CI]	AD [95% CI]	AF [95% CI]	AD [95% CI]
2009	3313	7.9 [2.9 - 12.6]	262 [97 - 418]	24.2 [9.5 - 36.4]	801 [316 - 1208]
2010	3189	8.0 [3.0 - 12.7]	255 [95 - 406]	24.2 [9.6 - 36.5]	773 [305 - 1165]
2011	2607	5.2 [1.9 - 8.4]	137 [50 - 220]	22.0 [8.6 - 33.4]	573 [224 - 871]
2012	2400	4.1 [1.5 - 6.6]	98 [36 - 158]	21.0 [8.2 - 32.0]	504 [197 - 769]
2013	2338	4.2 [1.5 - 6.7]	97 [36 - 157]	21.1 [8.2 - 32.1]	493 [192 - 752]
2014	2208	-	-	17.5 [6.7 - 27.1]	387 [149 - 598]
2015	1936	-	-	13.5 [5.1 - 21.1]	261 [99 - 409]
2016	1907	2.4 [0.9 - 4.0]	46 [17 - 75]	19.7 [7.6 - 30.1]	375 [145 - 575]
2017	1790	6.1 [2.2- 9.7]	108 [40 - 174]	22.6 [8.9 - 34.3]	405 [159 - 615]
2018	1695	-	-	13.9 [5.3 - 21.7]	235 [89 - 368]
Total	23383	-	1003 [371 - 1608]	-	4807 [1875 - 7330]

Table ***8*** presents the environmental burden of disease associated with exposure to $PM_{2.5}$ concentrations above the NAAQS in the Nkangala district adult population. The first column shows the year, the second column indicates the number of death per year, the third column shows the percentage of attributable fraction (95% and confidence interval) of cardiopulmonary diseases related death and the fourth column indicates the number of death attributable to the exposure to $PM_{2.5}$ concentrations above the NAAQS in adults population in Nkangala district, the firth column shows the percentage of attributable fraction (95% and confidence interval) of cardiopulmonary diseases related death and the sixth column shows the number of death attributable to the exposure to $PM_{2.5}$ concentrations above the WHO guideline in adults population in Nkangala district. In 2009, there were 3,955 deaths due to cardiopulmonary disease in the adult population of Nkangala districts, accounting for 3.8% of the total deaths due to cardiopulmonary diseases in the adult population. This was equivalent to 150 deaths due to exposure to $PM_{2.5}$ above the NAAQS. In contrast, 20.8% of the total deaths due to cardiopulmonary diseases in the adult population were attributable to exposure to $PM_{2.5}$ above the WHO guideline, equivalent to 822 deaths. In total, there were 31,349 cardiopulmonary disease-related deaths in the adult population of the Nkangala district. Of these, 745 cardiopulmonary disease-related deaths were attributable to exposure to $PM_{2.5}$ above the NAAQS, and 5,941 cardiopulmonary disease-related deaths were attributable to exposure to $PM_{2.5}$ above the WHO guidelines.

Table 8: Environmental burden of disease in Nkangala district

		NAAQS		**WHO Guideline**	
Year	N death	AF [95% CI]	AD [95% CI]	AF [95% CI]	AD [95% CI]
2009	3955	3.8 [1.4 - 6.1]	150 [55 - 242]	20.8 [8.09 - 31.72]	822 [320 - 1255]
2010	3452	3.5 [1.3 - 5.7]	122 [45 - 198]	20.6 [8.01 - 31.43]	710 [276 - 1085]
2011	3304	4.1 [1.5 - 6.7]	137 [50 - 221]	21.1 [8.21 - 32.12]	696 [271 - 1061]
2012	3083	1.4 [0.5 - 2.3]	43 [16 - 71]	18.8 [7.28 - 28.93]	580 [224 - 892]
2013	3027	0.7 [0.2 – 1.1]	20 [7 - 33]	18.2 [7.02 - 28.06]	551 [213 - 849]
2014	3222	-	-	13.3 [5.03 - 20.82]	428 [162 - 671]
2015	2993	0.8 [0.3 - 1.3]	24 [9 - 39]	18.3 [7.07 - 28.20]	548 [212 - 844]
2016	2912	-	-	15.4 [5.86 - 23.90]	447 [171 - 696]
2017	2658	5.1 [1.9 - 8.3]	136 [50 - 220]	21.9 [8.56 - 33.28]	582 [228 - 885]
2018	2743	4.1 [1.5 - 6.6]	113 [41 - 182]	21.1 [8.20 - 32.09]	577 [225 - 880]
Total	31349	-	745 [273 - 1206]		5941 [2302 – 9118]

The environmental burden of disease analysis demonstrates the health implications of chronic exposure to $PM_{2.5}$. There were a total of 23,383 and 31,349 deaths due to cardiopulmonary diseases in adults above 30 years from 2009 to 2018 in the Gert Sibande district and Nkangala district, respectively. A high number of mortalities in the Nkangala district may be attributed to its higher population compared to the Gert Sibande district (StatsSA, 2018). An estimated 1,003 deaths were attributed to chronic exposure to $PM_{2.5}$ under NAAQS, whereas 4,807 were attributed to chronic exposure to $PM_{2.5}$ when the WHO guideline was used in the Gert Sibande district. An estimated 745 cardiopulmonary deaths in Nkangala districts could have been prevented under NAAQS, and 5,941 deaths under WHO guidelines, underscoring the substantial public health gains that could be achieved with stricter standards and effective pollution reduction. Myllyvirta (2014) estimated 2200 premature deaths per year due to exposure to $PM_{2.5}$ from coal-fired power stations. South African NAAQS are more lenient compared to WHO guidelines, resulting in systemic underestimation of risks. Given that the Mpumalanga Highveld is home to 12 out of 17 coal-fired power stations in South Africa, the findings provide clear evidence that current regulatory frameworks do not adequately protect public health.

4. Conclusion

This study demonstrates that long-term exposure to $PM_{2.5}$, PM_{10}, SO_2, and NO_2 in the Mpumalanga Highveld poses a significant health risk to adults, with particulate matter as the dominant contributor. $PM_{2.5}$ and PM_{10} exceeded SANAAQS and WHO guidelines in Mpumalanga Highveld for most of 2009 to 2018. As a result, adults faced non-carcinogenic risks almost every year; the WHO guidelines reveal far greater risks than the SANAAQS. Communities in Gert Sibande and Nkangala are exposed to unhealthy air for more than 75% of the days. Consequently, an estimated 10,748 cardiopulmonary deaths could have been prevented over 10 years if the WHO guidelines were met. The findings suggest an urgent need to review South Africa's NAAQS to align more closely with the WHO guidelines.

Declaration of Interest Statement
The authors declare that they have no conflicts of interest.

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