Research article

Assessing fine particulate matter ($PM_{2.5}$) concentrations at a gold mine tailing facility and adjacent community

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Abstract

South Africa is home to some of the world's largest gold mines and contributes significantly to global gold production. However, gold mining activities generate waste in the form of soil, which is stored at Tailing Storage Facilities (TSFs). Gold mine TSFs are a source of ambient $PM_{2.5}$. $PM_{2.5}$ is particulate matter with a diameter of 2.5 micrometres or smaller. While many studies have documented the diurnal and seasonal variations of ambient $PM_{2.5}$, limited studies have reported these variations at the source and receptor. This study aimed to assess the variations in $PM_{2.5}$ at the source (Evander Gold Mine TSF) and at the receptor (eMbalenhle community). Ambient $PM_{2.5}$ concentrations were monitored over a one-year period (07 February 2022 to 07 February 2023) using Clarity Node-S Low-Cost Monitors (LCMs). Meteorological data (wind speed, wind direction, solar radiation, atmospheric radiation, rain, relative humidity, and temperature) for the same period were sourced from the South African Air Quality Information System (SAAQIS). Statistical analyses were performed using the Openair packages in R Studio (version 4.0.2) and Stata software (version 18). The results showed that $PM_{2.5}$ concentrations were higher in winter and lower in summer at the community site and gold mine TSF. The average 24-hour $PM_{2.5}$ concentrations at the community site and gold mine TSF were 19.24 and 9.70 $\mu g/m^3$, respectively. The daily $PM_{2.5}$ concentrations at the community site exceeded the South African National Ambient Air Quality Standard (NAAQS) of 40 $\mu g/m^3$ 26 times and the WHO guidelines of 15 $\mu g/m^3$ 181 times. The daily (24-hour) NAAQS was not exceeded at the gold mine TSF; however, the WHO guideline was exceeded 85 times. Diurnal $PM_{2.5}$ variations in the community showed a bimodal pattern, with peak concentrations occurring early in the morning (05:00) and late afternoon (16:00). Although the higher $PM_{2.5}$ concentrations were recorded in the community compared to the gold mine TSF, local $PM_{2.5}$ sources may have contributed to the elevated concentrations. It is recommended that future studies focus on the dispersion and source apportionment of $PM_{2.5}$ to quantify the contribution of various sources in eMbalenhle.

Keywords

Low-cost monitors, particulate matter, gold mining, meteorological data

Introduction

Gold mining plays an important economic role, providing employment and income opportunities (Wale et al., 2021). Despite the importance of these mines, they are a source of particulate matter with a diameter of 2.5 micrometres or smaller called $PM_{2.5}$. They include a mixture of solids and liquid droplets (Ahrens, 2015). Gold mine Tailing Storage Facilities (TSFs) include residues of gold extraction processes and sand particles. The residues are discharged into a pond to accumulate and form a dam (Been, 2016). Following dam formation, wind erosion and mechanical processes break down the soil and emit $PM_{2.5}$ into the atmosphere (Ojelede, 2012). Fine particles ($PM_{2.5}$) may also originate from industrial processes, vehicular emissions (Tian et al., 2021), power plants (Bai et al., 2020) and natural processes (Kim et al., 2019). The inhalation of $PM_{2.5}$ can lead to asthma, lung disease and chronic obstructive pulmonary disorder (Wang and Liu, 2023). The most influential factor affecting human health is particle size (Chen et al., 2017). Small particles penetrate deeper into the respiratory system (Losacco et al., 2018). Studies have indicated that smaller particles are more toxic than larger particles with the same composition. This is due to their high deposition efficiency on the respiratory tract (Sonwani et al., 2021).

Ambient PM$_{2.5}$ concentrations generally peak in the early mornings and evenings due to increased human activities (Chen et al., 2020). Furthermore, temperature inversions and reduced dispersion in the morning and evening lead to increased ground-level PM$_{2.5}$ concentration (Niedźwiedź et al., 2021). Diurnal PM$_{2.5}$ concentrations vary across locations due to local and regional sources (Fu et al., 2020). In most urban areas, PM$_{2.5}$ concentrations are higher during winter, primarily due to increased residential cooking, use of traditional fuels for heating and atmospheric conditions (Xu et al., 2020). On the other hand, summer seasons have lower PM$_{2.5}$ concentrations due to increased rainfall and improved dispersion (Sharma et al., 2022).

Once PM$_{2.5}$ is released into the atmosphere, wind transports it over long distances (Kim et al., 2021; Cheng and Hsu, 2019). Wind speed, wind direction, atmospheric stability and humidity influence the dispersion patterns of PM$_{2.5}$. Higher wind speeds transport PM$_{2.5}$ over long distances. Low wind speeds allow PM$_{2.5}$ to accumulate near the sources. Wind direction determines the travel of PM$_{2.5}$ to surrounding communities (Hu et al., 2022; Ma et al., 2021). Stable atmospheric conditions trap PM$_{2.5}$ near the ground, whereas unstable air helps disperse it vertically and horizontally. In addition, humidity causes PM$_{2.5}$ to absorb moisture and grow (Sirithian et al., 2022).

Most studies have used high-resolution ambient air quality data from monitoring stations to determine diurnal and seasonal PM$_{2.5}$ trends (Tian et al., 2019; He et al., 2020; Yatkin et al., 2020). The high-resolution data have a high level of precision in terms of spatial, temporal and spectral (Hu et al., 2014). The concentrations recorded at the ambient air monitoring stations are assumed to indicate what communities are exposed to. However, the spatial resolution of airborne PM$_{2.5}$ can be improved if a network of ambient monitoring stations covers a larger area (Squizzato et al., 2017). This is achieved by using a network of Low-Cost Monitors (LCMs) (Wendt et al., 2019).

These monitors are readily deployed at multiple locations to account for spatial variability (Liu et al., 2019). The monitors are small, lightweight and have minimal power consumption compared to high-resolution ones (Johnson et al., 2018). However, the quality of data collected by LCMs may be arguable (Han et al., 2016). Most LCMs do not directly quantify particle mass concentrations; instead, they measure the number of particles in the air (Li and Biswas, 2017). Although the LCMs only provide particle number concentration, the recorded concentrations are converted to PM$_{2.5}$ mass concentrations using regression algorithms and equations (Han et al., 2016).

This study provided one of the first assessments of PM$_{2.5}$ concentrations at a gold mine TSF and the nearby community using LCMs. It demonstrated the capability of LCMs to capture spatial variability in PM$_{2.5}$ at the source and receptor. The findings contribute new evidence on the potential networks of LCMs for environmental monitoring in resource-limited settings and in areas where high-resolution monitors are scarce.

Materials and methods

Study areas

The gold mine TSF in Evander (-26.483319° S; 29.095546° E) and the community of eMbalenhle (-26° 550613° S; 29.078937° E) were chosen as the source and the receptor, respectively. Both areas fall under Govan Mbeki Municipality, in the south-eastern part of Mpumalanga Province. Evander and eMbalenhle are part of the Greater Secunda. The Municipality has the most diversified economy, dominated by the petrochemical industry, coal and gold mines (Govan Mbeki Municipality, 2021). The climatic conditions in both areas are characterized by a warm and temperate atmosphere. During the winter season, precipitation levels are lower compared to those experienced in summer (Trenberth, 1999).

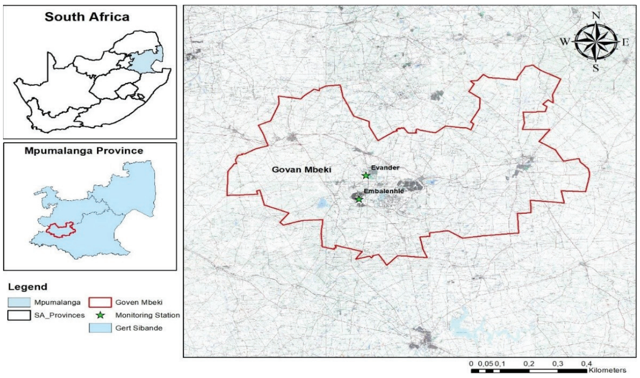

Figure 1: *Map indicating the study area and location of the low-cost monitors.*

The population of eMbalenhle is estimated to be 118 889, with an annual growth of 2.5% (Statistics South Africa, 2011). The community of eMbalenhle resides next to Evander Gold Mine TSF (Figure 1). eMbalenhle and Evander fall within the Highveld Priority Area (HPA). The HPA is an air pollution hotspot declared in terms of Section 18 of the National Ambient Air Quality Act (NEMAQA) (Act 39 of 2004).

Data collection

In this study, PM$_{2.5}$ concentrations were measured at the gold mine TSF and in the community of eMbalenhle (Figure 1) over a one-year period (from 07 February 2022 to 07 February 2023) using the Clarity Node-S LCMs. The PM$_{2.5}$ concentrations were measured every 15 minutes in micrograms per cubic meter (µg/m^3) and averaged hourly. The LCMs use a light scattering method with remote calibration. They have solar panels and batteries that can last up to 15 days in total darkness (Clarity Movement, 2023). The data was available on the website (https://dashboard.clarity.io/overview), Apple and Android applications.

Meteorological and PM$_{2.5}$ data for the same period were obtained from the monitoring station situated in eMbalenhle which is managed by the South African Weather Services (SAWS). The data was downloaded from the South African Air Quality Information System (SAAQIS) website, which is also managed by SAWS. The high-resolution monitoring station is located within the community. The high-resolution $PM_{2.5}$ data from the monitoring station situated in the community was used as reference data to compare and validate the data collected with the LCMs. The meteorological data included wind speed, wind direction, solar radiation, atmospheric radiation, rain, relative humidity and temperature. Wind speed and wind direction were used in the analysis to assess dispersion patterns of $PM_{2.5}$ concentrations. Although additional meteorological variables were available from the monitoring station, they were not included in the final analysis. However, the variables were used to understand the overall atmospheric conditions in the study area. The study period was divided into four seasons: Summer (December to February), Autumn (March to May), Winter (June to August) and Spring (September to November).

Data correction and validation

The data sets underwent a quality control process as described by Clarity Movement (2024) to ensure that the monitored (both $PM_{2.5}$ data sets monitored with the LCMs at the community and gold mine TSF) and reference data ($PM_{2.5}$ data monitored by the monitoring station) were not erroneous. Data correction and validation for the LCMs involved the use of machine learning algorithms to accurately predict $PM_{2.5}$ concentrations. The first step involved using a training dataset to teach the model to identify patterns (Malings et al., 2019). The model learned from the training dataset by adjusting its parameters to make predictions as accurate as possible (Kleine-Deters et al., 2017). Furthermore, cross-validation was employed to evaluate the model's performance (Wang et al., 2019). Clarity Movement developed custom calibration algorithms for each network and pollutant (Clarity Movement, 2024). The $PM_{2.5}$ concentrations were normalized by dividing each time series by the mean value (Qu et al., 2020).

Data management

The South African National Accreditation System (SANAS) criteria for the representativeness of air quality measurements were used to assess the validity of the monitored data (SANAS, 2018). The SANAS requires 90% data completeness. A completeness threshold of 90% was applied to calculate the hourly average from the $PM_{2.5}$ data monitored with the LCMs and the one obtained from the monitoring station. The validity percentage of the $PM_{2.5}$ data monitored with the LCMs and the one extracted from the SAAQIS were 80.1% and 63.1%, respectively. The data were organised in Microsoft Excel sheets and named according to various variables. Data cleaning was unnecessary since the instrument did not record negative and zero values.

Data analyses

Statistical analyses were performed using the Openair packages in R Studio (version 4.0.2) and Stata software (version 18). A non-parametric Wilcoxon signed-rank test was conducted to determine whether there were significant differences in $PM_{2.5}$ concentrations between the community and the gold mine TSF for both hourly and 24-hour averages.

Results

Hourly concentrations at community and gold mine TSF

The $PM_{2.5}$ hourly trends at both the community site and gold mine TSF showed variations in concentrations (Figure 2a). The highest hourly $PM_{2.5}$ concentrations were recorded during the early mornings (between 04:00 (22.23±20.51) and 05:00 (24.94±24.45) and late afternoons (between 16:00 (36.03±35.74) and 18:00 (31.77±35.57). At the community site, $PM_{2.5}$ concentrations had a distinct pattern with peaks in the mornings and evenings compared to those observed at the gold mine TSF (Figure 2b). At the gold mine TSF, the hourly $PM_{2.5}$ concentrations decreased between 10:00 (10.23±7.64) and 16:00 (10.70±10.10). The $PM_{2.5}$ concentrations increased between 17:00 (11.30±11.93) and 20:00 (08:30±08:75) at the gold mine TSF.

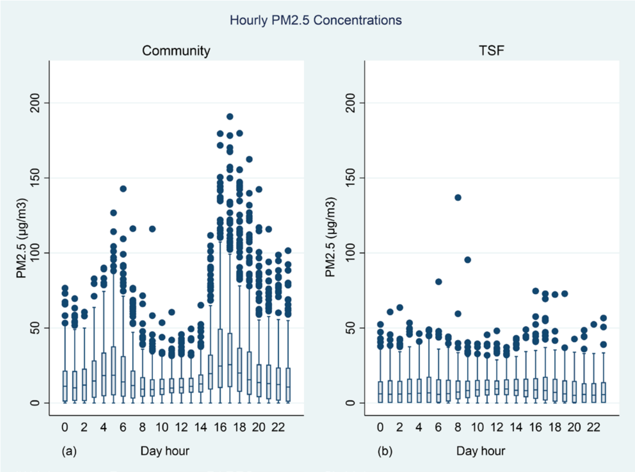

Figure 2: *Hourly* $PM_{2.5}$ *concentrations at the (a) community and (b) Gold Mine TSF.*

Daily $PM_{2.5}$ concentrations at the community and gold mine TSF

The daily (24-hour) $PM_{2.5}$ concentrations at the community and gold mine TSF are shown in Figure 3. The average daily (24-hour) $PM_{2.5}$ concentrations at the community site and gold mine TSF were 19.24 and 9.70 µg/m^3, respectively. The daily $PM_{2.5}$ concentrations at the community site exceeded the South African National Ambient Air Quality Standard (NAAQS) of 40 µg/m^3 26 times and the World Health Organisation (WHO) guideline of 15 µg/m^3 181 times (Figure 3a). A maximum of 4 exceedances per year is permitted for compliance with the NAAQS. The daily (24-hour) NAAQS was not exceeded at the gold mine TSF. However, the WHO guideline was exceeded eighty-five (85) times (Figure 3b). At the community site, the 24-hour NAAQS exceedances were observed more frequently in June (7 exceedances) and July (12 exceedances), with the highest value of 63.23 µg/m^3 recorded on 7 July 2022.

Table 1 presents the descriptive statistics of hourly and 24-hour $PM_{2.5}$ concentrations over the entire monitoring period at both

Table 1: *Descriptive statistics of the $PM_{2.5}$ concentrations at the community and gold mine TSF*

Duration	Data points	Mean	Std. Dev.	Median	1st Quartile	3rd Quartile	Min	Max	IQR
	N	$PM_{2.5}$ (μg/m³)		$PM_{2.5}$ (μg/m³)	$PM_{2.5}$ (μg/m³)	$PM_{2.5}$ (μg/m³)	$PM_{2.5}$ (μg/m³)	$PM_{2.5}$ (μg/m³)	
Community hourly	7,511	18.87*	21.74	12.87	4.99	24.55	0.01	190.91	19.56
TSF hourly	8,735	9.69*	9.68	7.47	1.04	15.46	0.01	136.92	14.42
Community 24-hr	7,887	19.27**	13.61	16.94	8.21	27.12	1.69	64.43	18.91
TSF 24-hr	8,748	32.26**	16.52	32.43	18.46	44.44	0.14	99.15	25.98

*$p<0.001$
**$p<0.0001$

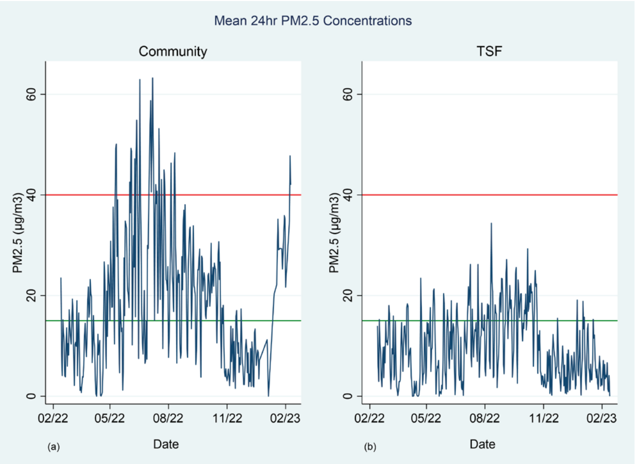

Figure 3: *24-Hour $PM_{2.5}$ concentrations at the (a) community and (b) Gold Mine TSF.*
**Red line: South African 24-hour NAAQS for $PM_{2.5}$ (40 μg/m³)*
**Green line: WHO 24-hour guideline for $PM_{2.5}$ (15 μg/m³)*

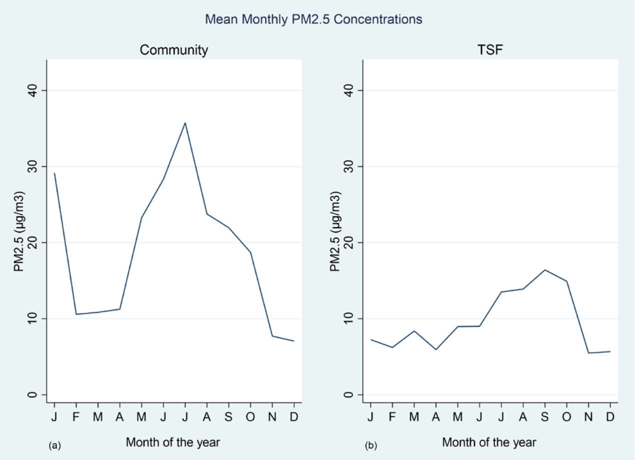

Figure 4: *Monthly $PM_{2.5}$ concentrations at the (a) community and (b) Gold mine TSF.*

the community site and the gold mine TSF. The hourly $PM_{2.5}$ concentrations in the community had a median of 12.87 μg/m³ (IQR: 19.56 μg/m³), much higher than that of the gold mine TSF (7.5 μg/m³ (IQR: 14.42 μg/m³)). The 24-hour $PM_{2.5}$ concentrations in the community had a median of 16 μg/m³ (IQR: 18.91 μg/m³), lower than that of the gold mine TSF (32.4 μg/m³ (IQR: 25.98 μg/m³)).

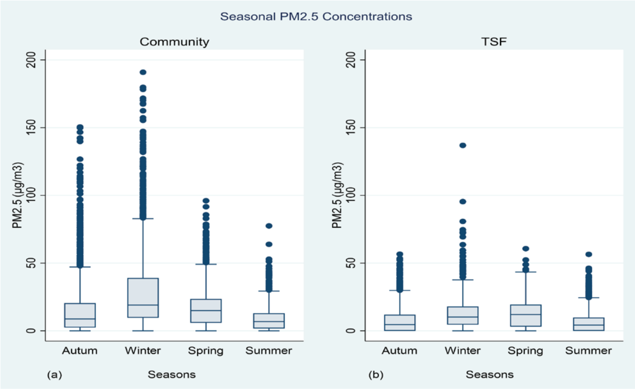

Figure 5: *Seasonal $PM_{2.5}$ concentrations at the (a) Community and (b) Gold Mine TSF.*

Monthly $PM_{2.5}$ concentrations at the community and gold mine TSF

The monthly $PM_{2.5}$ concentrations at the community and gold mine TSF are indicated in Figure 4. At the community site (Figure 4a), the lowest $PM_{2.5}$ concentrations were observed in December (7.06±3.64 μg/m³), followed by November (7.71±5.51 μg/m³). At the gold mine TSF (Figure 4b), the lowest $PM_{2.5}$ concentrations were recorded in November (5.51±3.83 μg/m³), followed by December (5.59±4.22 μg/m³). The highest $PM_{2.5}$ concentrations were observed in July at the community site and gold mine TSF. The $PM_{2.5}$ concentrations were 35.75±13.69 μg/m³ and 13.90±5.55 μg/m³ at the community site and gold mine TSF, respectively.

Seasonal variations of $PM_{2.5}$ concentrations at the community and gold mine TSF

The seasonal $PM_{2.5}$ concentrations at the community site (Figure 5a) and TSF (Figure 5b) are shown. $PM_{2.5}$ concentrations increased during winter (June to August) at both the community site and TSF compared to summer (December to February). The winter season showed the highest $PM_{2.5}$ concentrations at the community site (29.28 μg/m³) and TSF sites (12.38 μg/m³). Following the winter season's highest $PM_{2.5}$ concentrations, there was an increase in $PM_{2.5}$ concentrations during spring (September to November) at the community site (16.13±12.28) and 12.11±12.28 μg/m³ at TSF compared to autumn (March to May). In autumn, the $PM_{2.5}$ concentrations were 15.12±7.06 and 7.73±1.61 μg/m³ at the community site and TSF, respectively.

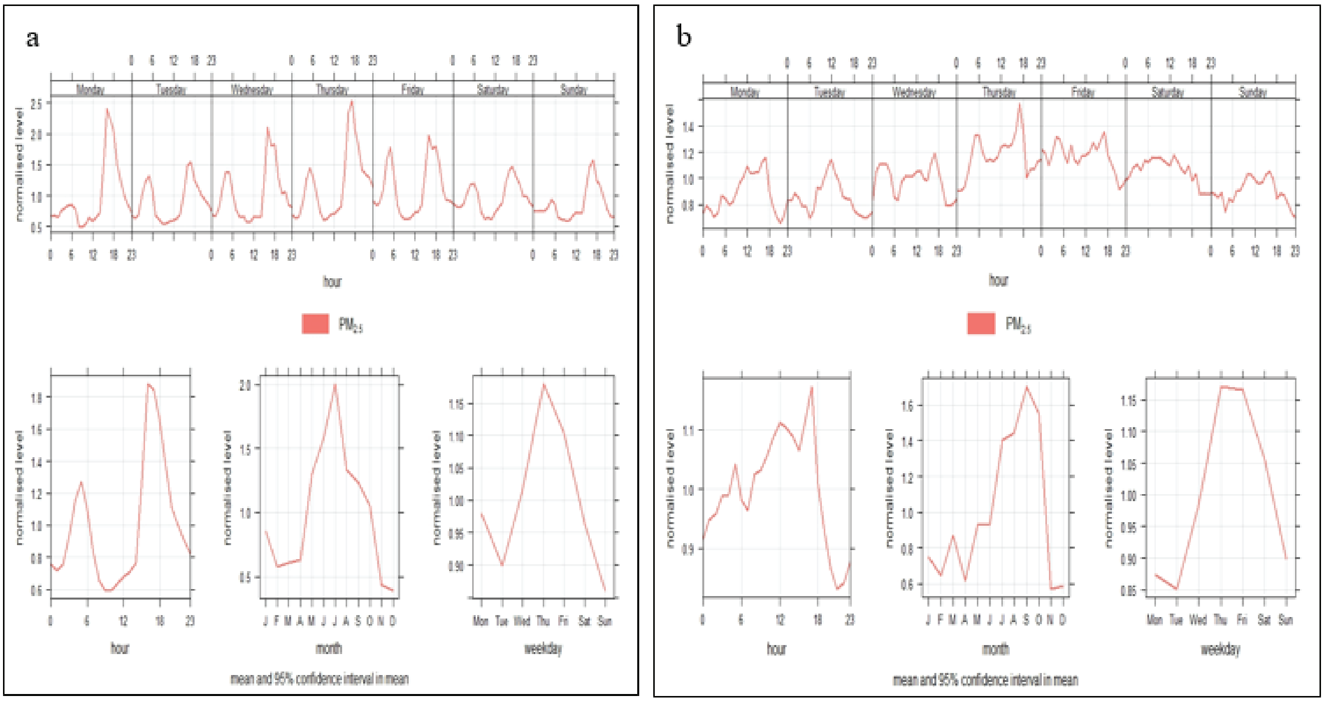

Figure 6: *Normalised PM$_{2.5}$ concentration trends at the (a) community and (b) Gold Mine TSF.*

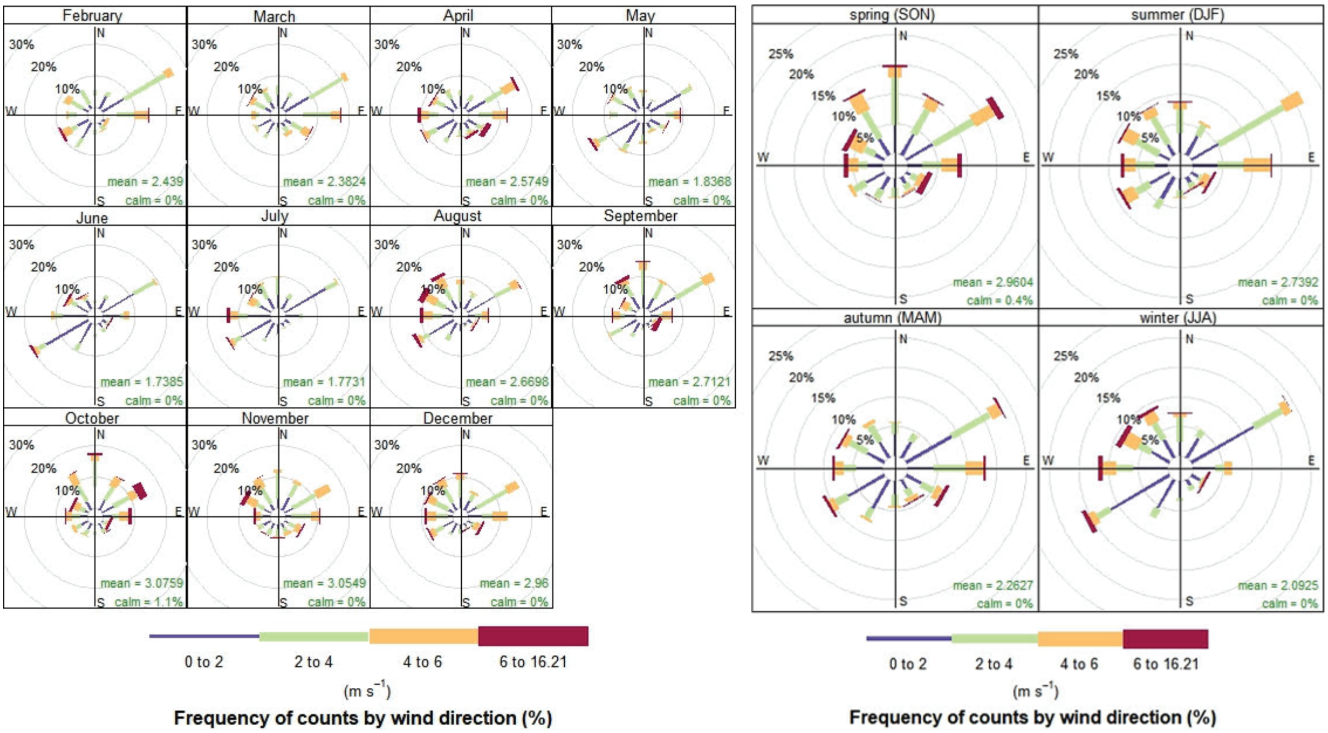

Figure 7: *Monthly (a) and seasonal (b) wind roses at the community site.*

Normalised trend analysis of PM$_{2.5}$ concentrations

There were variations in the hourly, diurnal and monthly PM$_{2.5}$ concentrations at the community site (Figure 6a) and TSF (Figure 6b). At the community site, the first peak was observed in the morning, with decreased PM$_{2.5}$ concentrations during the day (between 07:00 and 12:00). The second peak was observed in the afternoon and towards the evening (between 15:00 and 19:00), with PM$_{2.5}$ concentrations decreasing after 20:00. On the other hand, the PM$_{2.5}$ concentrations at the gold mine TSF increased from 08:00 to 12:00. There were reduced PM$_{2.5}$ concentrations on Saturday and Sunday mornings.

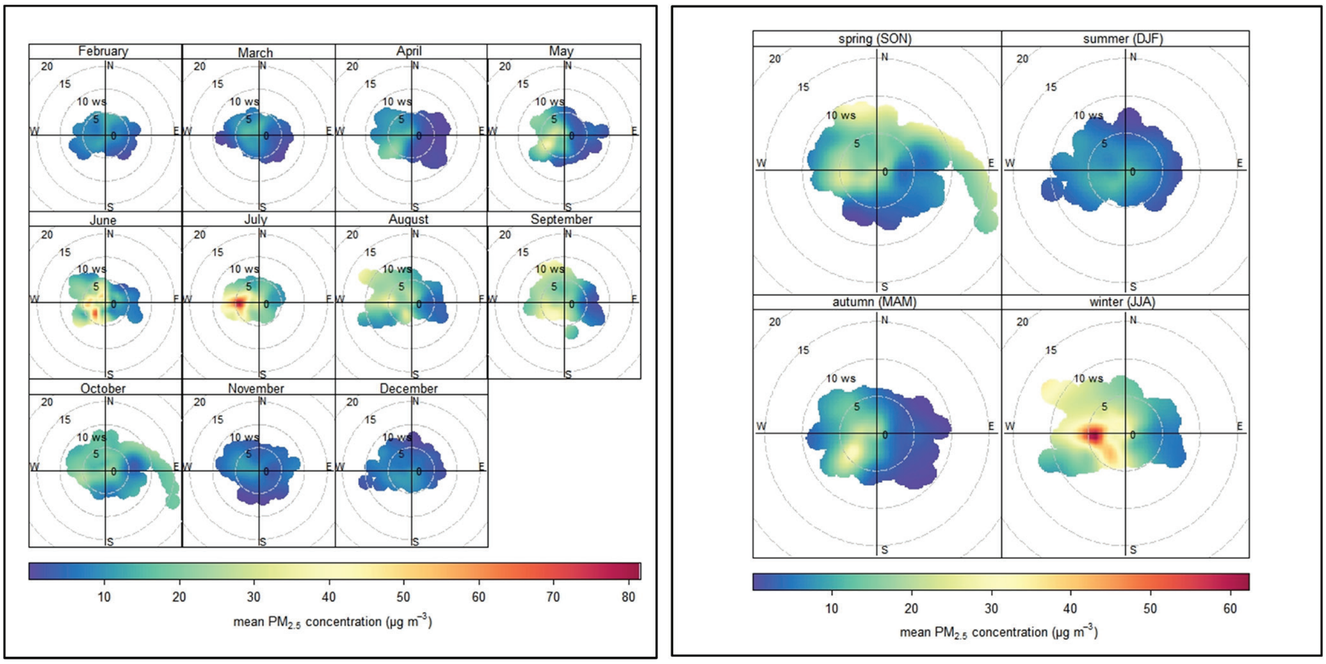

Figure 8: *Monthly (a) and seasonal (b) pollution roses for PM2.5 concentrations at the community site.*

Influence of meteorological conditions on $PM_{2.5}$ conditions

The monthly and seasonal wind roses at the community site are presented in Figures 7(a) and (b). The north-easterly winds contributed to the increased $PM_{2.5}$ concentrations at the receptor (community). The gold mine TSF is situated west of the eMbalenhle community. North-easterly winds prevailed in February, March, April, September, October, November and December. South-westerly winds were observed in May, June, July and August (Figure 7a). In spring and summer, the prevailing winds were mainly north-easterly (Figure 7b). South-westerly and north-easterly winds were observed in winter.

The $PM_{2.5}$ monthly and seasonal pollution roses at the community site are indicated in Figure 8(a) and (b). Concentrations of $PM_{2.5}$ were observed to be between 30 and 50 µg/m^3 in June, July and August, when the wind was predominantly from a south-westerly direction (Figure 8a). The concentrations decreased in summer with the wind coming from different directions. In winter, the increased $PM_{2.5}$ concentrations increased (ranging from 25 to 50 µg/m^3) with wind predominantly from north-westerly and south-westerly directions (Figure 8b).

Discussion

In this study, two LCMs were deployed for 12 months (07 February 2022 to 07 February 2023) at the source (gold mine TSF) and receptor (community of eMbalenhle). The validity of the LCMs was evaluated by comparing the $PM_{2.5}$ measurements against the data obtained from a collocated government ambient air monitoring station managed by SAWS. The variations in daily $PM_{2.5}$ concentrations were observed at both monitoring sites. The highest hourly $PM_{2.5}$ concentrations were recorded at the community site during the early mornings (between 04:00 and 05:00) and late afternoons (16:00) and evenings (18:00). The $PM_{2.5}$ concentrations decreased from midnight (00:00) to 03:00, followed by a morning peak and an evening peak late in the day (Figure 2). The morning peaks are attributed to vehicular traffic emissions (Majewski et al., 2011). The evening peaks appeared more pronounced than the morning ones (Figure 2). This finding disagrees with that of Bamola et al. (2024), who found that diurnal $PM_{2.5}$ concentrations were higher during the morning period (at 09:00) and lower in the early evening (between 16:00 and 17:00) in Taj City. A study conducted by Walton et al. (2021) on source apportionment of ambient fine and coarse aerosols in eMbalenhle found that dust, secondary aerosols, residential combustion, biomass burning and industries were the major sources. The $PM_{2.5}$ concentrations were higher on weekdays than on weekends, possibly due to increased traffic volumes during the morning rush hour (Figure 6). Liu et al. (2015a) contended that morning peaks are due to increased anthropogenic activities. This is evident from Figure 6, which shows reduced $PM_{2.5}$ concentrations on Saturday and Sunday mornings. Tong et al. (2020) found that vehicular $PM_{2.5}$ emissions were higher on weekdays than on weekends. The evening peaks are attributed to changes in meteorological patterns where the boundary layer height increases during the day. In the late afternoon, there was an increase in rush hour volume and other anthropogenic activities, leading to high evening peaks, as also observed by Liu et al. (2015a).

Given the complexity of factors affecting $PM_{2.5}$ concentrations, it is likely that concentrations would consistently be higher during weekdays and lower on weekends at both measuring sites. The living patterns of the people in the eMbalenhle community may have influenced this. A study by Feng et al. (2014) found that the diurnal and seasonal concentrations corresponded to the living styles of the people in the study area.

In contrast, the gold mine TSF did not show distinct bimodal diurnal patterns. Generally, the gold mine TSF experiences minimal human activity, resulting in consistent diurnal concentrations. Bimodal patterns are observed when an area experiences different concentrations with varying intensities from local sources during the day. (Liu et al., 2015b). Wind speed increases during the day due to surface heating from the sun, which in turn enhances atmospheric turbulence and vertical mixing. This may cause $PM_{2.5}$ concentrations from the gold mine TSF to be resuspended during the day (Figure 7). However, wind speeds are often reduced at night, leading to lower $PM_{2.5}$ concentrations (Park et al., 2021).

Meteorological conditions have an overwhelming impact on $PM_{2.5}$ concentrations. In this study, it was expected that the $PM_{2.5}$ concentrations at the source would be higher than those at the receptor (community). However, our findings contradict this expectation. In addition to the local sources, regional and long-distance transport of $PM_{2.5}$ due to wind patterns and atmospheric circulation could increase $PM_{2.5}$ concentrations in locations far from the sources (Li et al., 2020). The wind direction was predominantly north-easterly during the twelve (12) months of this study period (07 February 2022 to 07 February 2023). The community is situated towards the West of the gold mine TSF. This suggests that the gold mine TSF may not have made a significant contribution to the high $PM_{2.5}$ concentrations in the community. However, there is a need to undertake source apportionment to accurately determine the gold mine TSF's contribution to the affected community.

In the study sites, summer is mainly characterized by warm and rainy days. It is dry, cold, and sunny in winter with strong winds, especially in August. Autumn is characterized by cold and sunny early mornings, with long and warm days. The diurnal $PM_{2.5}$ concentrations varied based on seasonal changes (Mukta et al., 2020). At both study sites, the seasonal variability was higher during the winter and lower during the summer. This finding aligns with studies conducted elsewhere, which reported seasonal variability of $PM_{2.5}$, with the highest concentrations observed in winter and the lowest in summer (Javed et al., 2021; Watson et al., 2021; Indraj and Warpa, 2024). This could result from increased energy consumption and the use of traditional fuels, including biomass and coal, for cooking and space heating (Szatylowicz et al., 2023). A study by Thabethe et al. (2014) indicated that domestic fuel burning contributed to high concentrations of particulate matter in the eMbalenhle. Vehicular traffic, industrial emissions, construction, residential heating and cooking may release significant amounts of $PM_{2.5}$ into the atmosphere (Dai et al., 2022; Naidja et al., 2022). Another study found that residential combustion contributed 9% to 13% and 14% to 23% of $PM_{2.5}$ during winter in eMbalenhle (Walton et al., 2021). Furthermore, as urbanization and industrialization increase, there is the potential for increased $PM_{2.5}$ concentrations in densely populated areas (He et al., 2023). However, these findings contrast with those of Liu et al. (2015a), who found higher $PM_{2.5}$ concentrations in the spring and summer months. This increase was attributed to changes in concentration, long-range transport patterns, and meteorological conditions. The decrease in $PM_{2.5}$ during the winter months was attributed to fuel switching during heating periods from coal-powered systems to natural gas (Liu et al., 2015a). In contrast, the summer months at both sites had lower $PM_{2.5}$ levels due to increased temperature and changes in the consumption and use of traditional fuels for heating. Again, meteorological conditions played a role in dispersing, diluting and reducing $PM_{2.5}$ concentrations during summer (Xin and Sun, 2022).

Conclusion

The results presented in this manuscript are from a one-year monitoring campaign at a gold mine TSF and a nearby community. The results revealed that daily $PM_{2.5}$ concentrations at the community site exceeded the 24-hour South African NAAQS of 40 µg/m^3 and the WHO guideline of 15 µg/m^3. However, this study could not confirm if the gold mine TSF was the main contributor to local air pollution. Therefore, additional studies focusing on source apportionment are needed to ascertain this uncertainty. Due to reported exceedances of the NAAQS and WHO guidelines, a study assessing the risk of exposure to $PM_{2.5}$ amongst residents of eMbalenhle is recommended.

The wind profile appeared to significantly contribute to the variation of $PM_{2.5}$ concentrations at the gold mine TSF. Local sources largely contribute to $PM_{2.5}$ concentrations at the community site. An increase in $PM_{2.5}$ concentrations indicates continued anthropogenic activities and ineffective strategies for managing air quality in the region. An analysis of one-year $PM_{2.5}$ trends at the gold mine TSF and the community may not be adequate if the other contributing sources are not considered. It is recommended that the $PM_{2.5}$ measurements should be conducted for at least 72 months (5 years), and multiple LCMs be deployed at each site to increase the spatial resolution of the measurements. This is because the $PM_{2.5}$ concentrations can vary significantly in time and space. This will enable a more comprehensive understanding of the $PM_{2.5}$ variations between the source and the receptor. The results clearly indicated that the measures aimed at reducing vehicular, combustion and other anthropogenic $PM_{2.5}$ would significantly reduce pollution levels in the eMbalenhle community. Area dust management controls and systems must be implemented and maintained to reduce $PM_{2.5}$ concentrations.

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Authors' contributions

This study is part of Ms Nomsa Thabethe's PhD at the University of the Witwatersrand. Ms Nomsa Thabethe drafted the manuscript and analysed the data. Conceptualization: NT, DM, and DB; data collection and analysis: NT; preparation of the manuscript: NT; editing and proofreading: TM; review and supervision: TM, DM, and DB.

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Ethical considerations

The study was approved by the University of the Witwatersrand Human Research Ethics Committee [HREC] (No: HRECNMW21/05/09).

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