

# Research article

## Quantifying the Air Quality Benefits of a Waste Collection Offsetting Intervention in the Vaal Triangle Airshed Priority Area (VTAPA)

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### Abstract

This paper presents the first-of-its-kind quantification of air quality benefits from a waste collection intervention in South Africa, using South African-based emission factors and dispersion modelling. Air pollutants are released from the open burning of unrecycled municipal solid waste (MSW). This study focused on waste collection in the Zamdela township, Sasolburg, within the Vaal Triangle Airshed Priority Area (VTAPA), using emission factors published by Wang et al. (2023) and waste collection quantities over 3 years from 2018 to 2020. Emissions from the waste skips were simulated in the CALPUFF dispersion model to assess impacts on air quality within the ambient environment. Several dispersion modelling scenarios based on different receptor configurations (i.e. ring, regular gridded and discrete) were investigated. From the total mass of waste collected over the period (13,798 tons), average emission rates of 3.27 tons of SO<sub>2</sub>, 25.04 tons of PM<sub>10</sub>, and 23.66 tons of PM<sub>2.5</sub> were calculated using the applied emission factors. The ring receptor configuration generally predicted higher ambient concentrations for all pollutants over the various averaging periods. This study highlights the benefits of the waste collection offsetting intervention for ambient air quality.

### Keywords

Open waste burning, municipal solid waste, offsetting, receptors, emission factors, ambient air quality benefit

### Introduction

The open burning of municipal solid waste is a significant source of air pollution, particularly in developing-world cities and is known to emit gaseous and particulate pollutants. The nature of pollution emitted is mainly dependent on the composition of the waste material (Wang et al., 2023; Wiedinmyer, 2014). The literature identifies CO, PM, NO<sub>x</sub>, SO<sub>2</sub>, VOCs, and hazardous air pollutants as primary pollutants of concern from open burning of solid waste (Lemieux et al., 2000; Christian et al., 2010).

Open burning of municipal solid waste can trigger health impacts such as acute and chronic respiratory disease, heart diseases, and allergic hypersensitivity (Das et al., 2018, Krecl et al., 2021) and also contribute to the deterioration of air quality. The harmful emission effects of open burning from solid waste combustion on human health were studied by (Kodros et al., 2016), who attributed premature adult mortality to chronic exposure to PM<sub>2.5</sub>. Emissions from open burning that impact

air quality and human health are also documented within the literature (e.g., Chaudhary et al., 2022).

Sutton et al. (2022) suggested that phasing out and reducing open waste burning in African urban areas would yield significant health and environmental benefits, in addition to regional reductions in greenhouse gas emissions.

Langerman et al. (2016) identified open waste burning as a significant contributor to air pollution in South Africa, worsening ambient air quality and causing health impacts. Haywood et al. (2021) identified open dumping and burning of solid waste as a common practice and widespread issue in South Africa.

Township communities in South Africa lack access to essential services, including refuse removal. As such, municipal solid waste management is a significant environmental and public

health problem in growing townships (Rasmeni & Madyira, 2019). As township populations in South Africa continue to increase, they will likely generate more waste. If poor waste collection persists, waste generation and open burning practices will become unavoidable.

Suppose municipal waste is not collected and burned for disposal. In that case, the probability of air pollution from the open burning of waste will likely compound the effects of air pollution from domestic fuel burning and continue contributing to the ambient air pollution burden, especially within townships.

Although previous studies focused on quantifying and assessing these pollutants, some notable assumptions were utilised. For example, the emissions inventory from the second-generation Vaal Priority Area airshed study (2020) for open burning of waste emissions was based on emissions factors from the literature published by Wiedinmyer, Yokelson and Gullett (2014) and local activity data based on estimates of waste collection per person (Emfuleni Municipality). Information on waste composition was taken from a study published by Jeffares & Green (Pty) Ltd (2016). The study identified limited literature on local emission factors for waste burning and the need for further research.

This study improved upon previous approaches by modelling emissions quantified from recently published South African emission factors (Wang et al., 2023) and measured activity data from waste skips in Zamdela throughout the period. The results are thus provenanced and realistically reflect the benefits to ambient air quality from the intervention.

## Methodology

### Study region

Zamdela township is located within the Sasolburg airshed, situated on the outskirts of Sasolburg, in the Metsimaholo municipality in the Fezile Dabi District in the Free State Province. The Sasolburg airshed resides within the VTAPA, an industrialised region of the South African Highveld.

Although VTAPA's population exceeds 3 million, Zamdela has approximately 90,000 inhabitants. It has a high unemployment rate, with more than 16,000 residents living in informal settlements (RYSE, 2017). Amelia and Iraq are sub-places within Zamdela.

The waste collection intervention was implemented in the suburbs of Amelia and Iraq, where waste collection services are poor within the Zamdela settlement.

### Emissions from open waste burning

Limited work has been done to develop emission factors for unrecycled municipal solid waste. Ramadan et al. (2022) undertook a comprehensive review of domestic waste burning, focusing on trends, methodologies, and emission factors for both developing and developed countries. Within Africa, most

research on this topic has been conducted in Nigeria, Ghana, Ethiopia, and Kenya, with limited research in South Africa.

Empirically derived emission factors based on representative country-specific waste profiles are required to quantify emissions from the open burning of solid waste and develop accurate emission inventories. A bottom-up methodology is applied to quantify atmospheric emissions of PM and SO<sub>2</sub> from open waste burning. The total emissions for both PM<sub>10</sub> and SO<sub>2</sub> were quantified based on the total waste collected over the period (13,798 tons) and applying the South-African-specific emission factors (Wang et al, 2023) for each pollutant using the following equation:

$$Ep = AR \times EFp \tag{1}$$

Where *Ep* is the total avoided emission of pollutant *p* (in metric tons per year); *AR* is the activity rate, i.e., the amount of burned waste avoided due to its collection (in tons per year); and, *EFp* is the emission factor of pollutant *p* per unit of waste (in g-emissions/kg-waste).

Waste streams from Zamdela were collected in 2019 (Figure 1). These were transported to the Desert Research Institute (DRI's research laboratory in Nevada for separation and analysis.



Figure 1: Municipal waste dumped within and alongside a waste skip in Amelia, Zamdela.

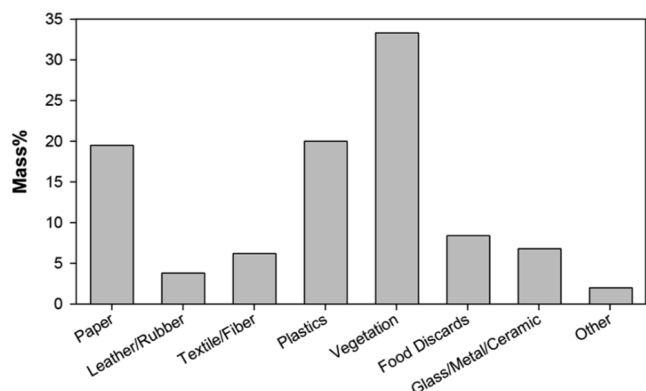


Figure 2: Fraction of Waste Streams in Zamdela (Wang et al., 2023).

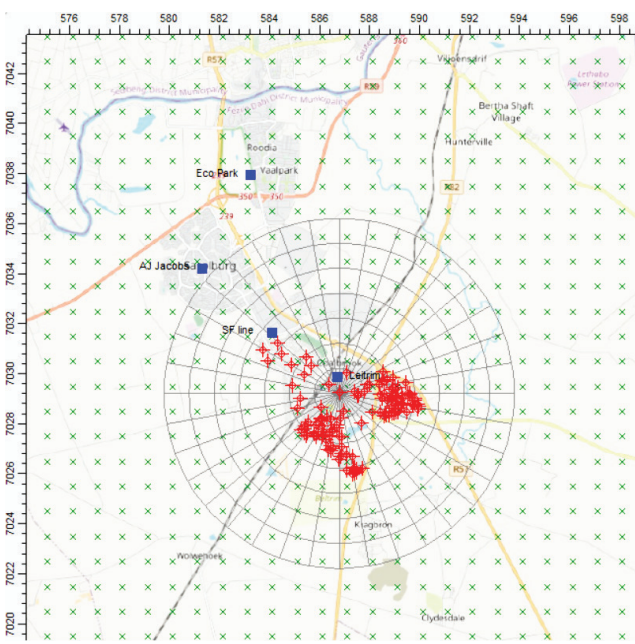
Based on field observations, Wang et al (2023) identified the composition and main categories of the waste streams as paper, plastic, organic food waste, and vegetation (Figure 2).

Combustion chamber testing was undertaken on the individual and combined waste streams to derive waste-specific emission factors. Mean emission factors for criteria pollutants were reported as 7.26 g/kg<sup>-1</sup> PM<sub>10</sub>, 6.86 g/kg<sup>-1</sup> PM<sub>2.5</sub> and 0.95 g/kg<sup>-1</sup> SO<sub>2</sub>, (Wang et al., 2023).

Activity rates (i.e., the amount of waste collected) were applied to these to determine total PM and SO<sub>2</sub> emissions (Table 1).

**Table 1:** Annual Waste collected and total emission of PM and SO<sub>2</sub> in Zamdela

Year	Mass (Kg)	Avg No of waste skips	PM <sub>10</sub> (tons)	PM <sub>2.5</sub> (tons)	SO <sub>2</sub> (tons)
2018	2420	85	17.6	16.6	2.3
2019	3305	121	24	22.7	3.1
2020	4368	150	31.7	30	4.2
2021	3703	158	26.9	25.4	3.5



**Figure 3:** Illustration of ring receptor(s) within the dispersion modelling application

### Meteorological data

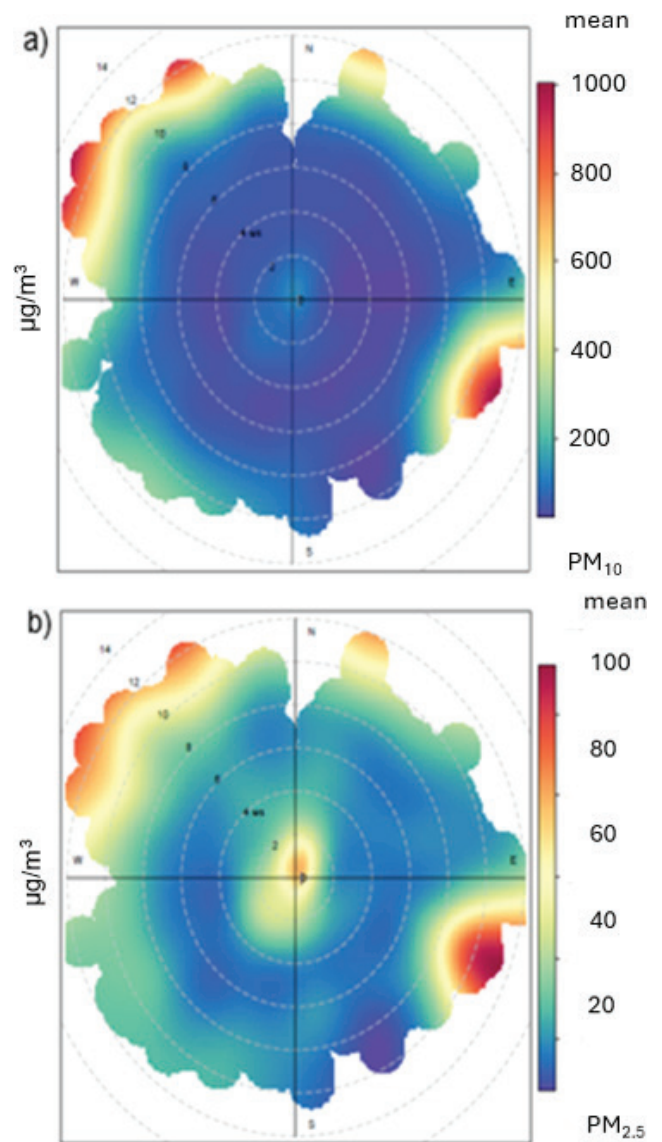
Gridded WRF meteorological data were used as input into the CALPUFF model over 3 years. Meteorological data were acquired from 2018 to 2020, including 2021, and model sensitivity simulations were conducted from July 2020 to July 2021. This included mesoscale data from the Weather Research and Forecasting (WRF) and CALMET diagnostic models.

### Receptor network

A multi-receptor configuration was modelled to predict

ambient concentrations and quantify net ambient air quality concentrations. Regular gridded receptors, as well as discrete and ring receptors, were selected and modelled. Regular receptors corresponded to the model's horizontal resolution (e.g., 1 km), whereas the proximity and locations of surrounding monitoring stations within the modelling domain determined discrete receptor locations. Ring receptors were also simulated to provide adequate spatial coverage over the emission sources. Ring receptors were placed at 1 km intervals from 1 km to 7 km in concentric circles in all directions, including 36 rays every 10 degrees. The ring receptor grid configuration is shown in Figure 3.

The ring receptor approach has been applied in previous near-field analyses in the CALPUFF model, (Tech, 2001; U.S. EPA; 1998; Carper and Ottersburg, 2003). The objective of utilising this approach within this study is to evaluate how model-predicted results compare against regular/gridded and discrete receptors.



**Figure 4:** Polar plot of PM<sub>10</sub> (a) and PM<sub>2.5</sub> (b) concentrations at the Leitrin AQMS (2019 – 2021).

## Results and discussion

### Analyses of ambient data

A statistical trend analysis of ambient air quality data over 3 years (2019 – 2021) was undertaken using the Openair R package (Carslaw, 2019) to understand likely source contributions based on measured pollutant data from the different AQMS site locations. Analyses of ambient monitoring data from local monitoring stations in the Sasolburg airshed provided insight into local source contributions to ambient pollution.

Trend analyses of ambient data from 3 monitoring stations were conducted to gain insight into the contributions of different sources. For brevity, we present high-level results from the Leitrim station in Zamdela, which is closest to the general location of the waste skips in Amelia and Iraq.

While elevated PM<sub>10</sub> concentrations were associated with higher wind speeds at some stations, attributable to PM from exposed areas (e.g., unvegetated surface cover), PM<sub>2.5</sub> concentrations were associated with lower wind speeds, suggesting the influence of localised sources (Figure 4).

A significant concentration of SO<sub>2</sub> is observed throughout the period. Observations of wind direction and high concentrations associated with high wind speeds were attributable to source influences from the power generation sector (indicative of tall-

stack contributions). In contrast, those related to low wind speeds were attributed to localised sources (Figure 5). The influence of tall-stack emissions is evident in the diurnal plot of SO<sub>2</sub>, with elevated concentrations peaking at midday, following steadily increasing concentrations from 07:00, peaking just before midday, and decreasing until 14:00.

These findings from the observed concentrations correspond to the recent work undertaken by (Feig et al., 2019).

### Receptor modelling results

Ambient impacts for PM and SO<sub>2</sub> were simulated for various averaging periods. Several dispersion modelling scenarios based on different receptor configurations were considered and evaluated. The ring receptor configuration indicated higher predicted ambient PM concentrations (i.e. 10.3 µg/m<sup>3</sup>) over the 24-hour averaging period (Figure 7) compared to the i) regular gridded receptor configuration (i.e. 4.9 µg/m<sup>3</sup>, Figure 6) and, ii) gridded receptor configuration (1 µg/m<sup>3</sup>) for PM<sub>2.5</sub>. The isopleth plots for PM<sub>10</sub> are not shown here, but showed a similar trend. Similarly, the ring receptor configuration indicated higher predicted ambient concentrations over the 1-hour averaging period (e.g., 5.7 µg/m<sup>3</sup>) compared to the i) regular gridded receptor (1.6 µg/m<sup>3</sup>) and ii) discrete receptor (1 µg/m<sup>3</sup>) modelling approaches. The use of the ring receptor configuration enabled modelled concentrations to be predicted over a larger target area around the emission sources throughout the modelling domain.

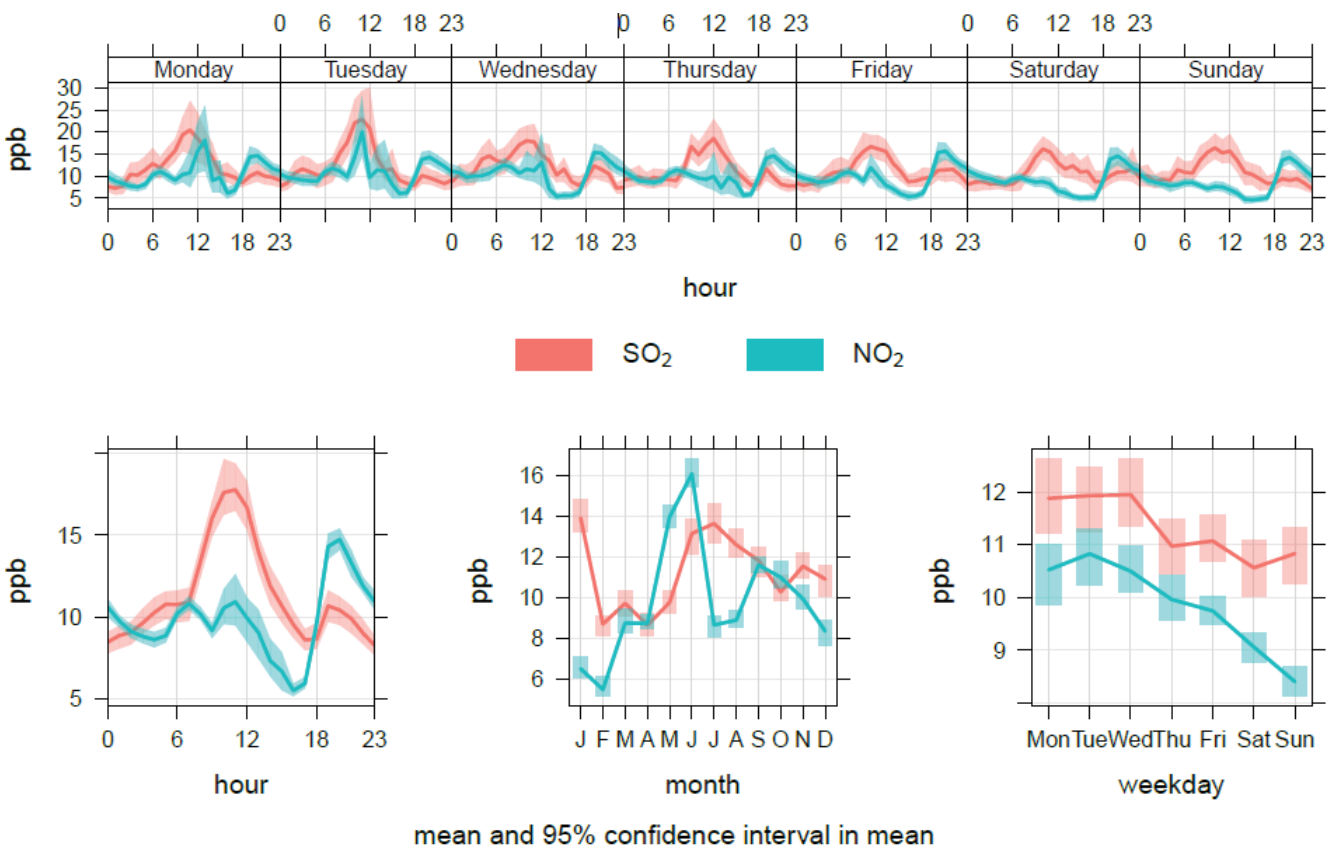


Figure 5: Time variation plot of SO<sub>2</sub> concentrations at the Leitrim AQMS (2019 – 2021)

When considering ground-level predictions based on the sampling grid, i.e., regular receptors (Figure 6), the model-predicted concentrations over short-term averaging periods indicate higher ambient air quality than those from the discrete receptor approach.

When using the ring receptor configuration to consider the dense proximity of all emission sources (waste skips) and the need to simulate model concentrations spatially within the immediate proximity to the waste skip sources, we found that higher model-predicted ambient concentrations occur within the immediate vicinity of where the waste skips are placed (Figure 7). The air quality impacts from waste burning in the ambient environment

are localised, within the vicinity of where open burning takes place. As such, a highly resolved receptor grid that accounts for this is required to quantify the ambient benefits on air quality.

### Assumptions and limitations

Noteworthy assumptions applied within the study included:

- Average emission rates were modelled for each pollutant, modelling the waste skips as point sources and assuming a continuous emission release throughout the period based on the waste emission (collection) profile. Emissions were apportioned to the waste skip locations within Zamdela and modelled over 3 years.

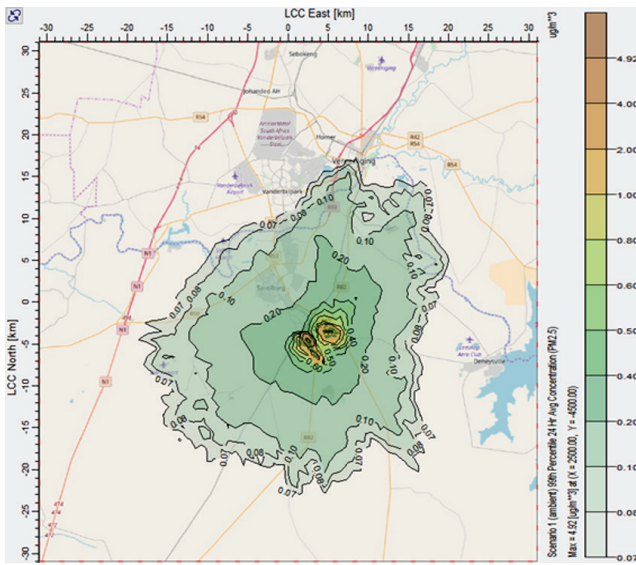


Figure 6: Isopleth plot for  $PM_{2.5}$  over a 24-hour averaging period (99<sup>th</sup> percentile) for all waste skip sources based on the regular receptor configuration

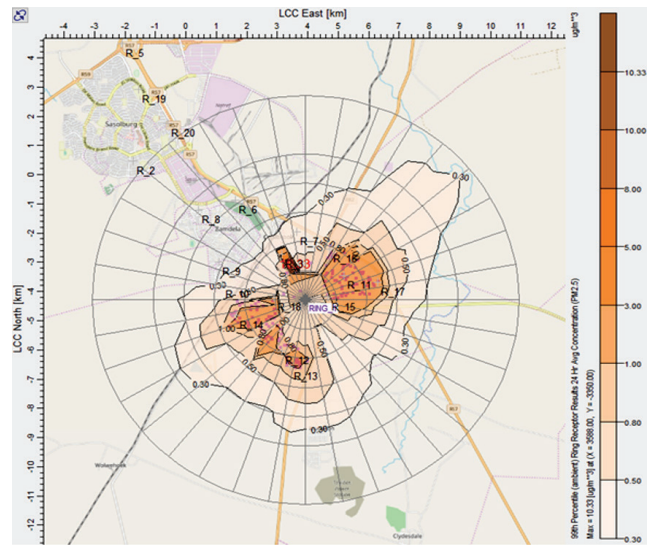


Figure 7: Isopleth plot for  $PM_{2.5}$  over a 24-hour averaging period (99<sup>th</sup> percentile) for all waste skip sources using the ring receptor approach

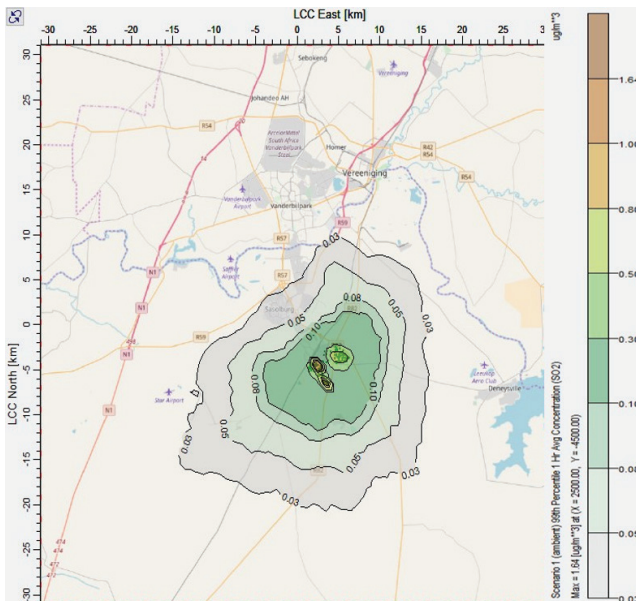


Figure 8: Isopleth plot for  $SO_2$  over a 1-hour averaging period (99<sup>th</sup> percentile) for all waste skip sources based on the regular receptor configuration

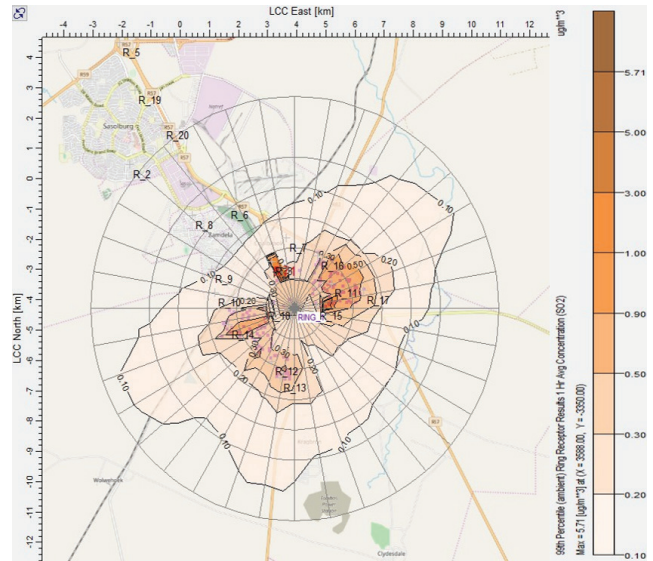


Figure 9: Isopleth plot for  $SO_2$  over a 1-hour averaging period (99<sup>th</sup> percentile) for all waste skip sources using the ring receptor approach

- The 99th percentiles were considered for the shorter averaging periods (i.e., 1 hour and 24 hours), thus, the modelled results for the short-term averaging periods can be regarded as conservative.
- This study focused on quantifying and modelling emissions from SO<sub>2</sub> and PM (both PM<sub>10</sub> and PM<sub>2.5</sub>) only, aligned to the target pollutants of the Offsetting intervention.

## Conclusion

This study quantified the benefits of ambient PM (PM<sub>10</sub> and PM<sub>2.5</sub>) and SO<sub>2</sub> for a waste collection offsetting intervention implemented in Zamdela. Although the waste collection intervention has been implemented over the last 8 years, we've focused on assessing the benefits to ambient air quality from 2018 to 2020. We utilised empirically derived emission factors based on waste compositions from Zamdela, derived from the Wang et al. (2023) study, to quantify total annual average emissions of 3.27 tons of SO<sub>2</sub>, 25.04 tons of PM<sub>10</sub>, and 23.66 tons of PM<sub>2.5</sub>. Emissions were apportioned in space and time in the CALPUFF dispersion model to predict ground-level concentrations.

Several dispersion modelling scenarios based on different receptor configurations were considered and evaluated. The ring receptor configuration indicated higher predicted ambient concentrations than the discrete and regular gridded receptor modelling approaches for PM and SO<sub>2</sub>. The use of the ring receptor configuration enabled modelled concentrations to be predicted in the immediate vicinity of the waste skips where open burning occurred and over a broader target area around the emissions sources throughout the modelling domain. The isopleths indicate a localised impact from sources close to and around the waste skips, highlighting the impact region for waste offsetting interventions.

Overall, ambient air quality benefits were determined from the waste collection intervention, regardless of the model's receptor configuration. The results from the dispersion modelling, in general, indicate that ambient concentrations within an already highly polluted airshed can be reduced and that improvements to ambient air quality can be achieved through the waste offsetting intervention.

This methodological approach, i.e., consideration of different receptor configurations, can be applied in future studies to accurately predict ambient concentrations from emission sources in the immediate vicinity of the intervention(s) being implemented. These are important in the context of the Offset principles' requirements for measuring the effectiveness of Offset interventions as outcomes-based, transparent, sustainable, measurable, and scientifically robust (DEA, 2014).

## Acknowledgements

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intervention used in the analyses of ambient data and in dispersion modelling simulations.

## Author contributions

Most of the work was conducted by Warren Carter, who was responsible for data processing, dispersion modelling, analysis, interpretation, and manuscript writing. Gregor Feig and Sandra De Vos assisted in interpreting data and editing the manuscript.

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