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*Research Paper*

# Dust deposition assessment at a Gold Mine Village in the West Rand: Gauteng Province of South Africa

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**ABSTRACT**

The windy season brings numerous community complaints for gold mining companies situated in the Witwatersrand due to windblown dust from tailings storage facilities (TSFs). For communities encroaching onto TSFs, windblown dust is perceived as a health hazard and an environmental challenge. In a study conducted in 2017 by the Lawyers for Human Rights, the community of a gold mine village perceives TSF6 and other surrounding tailings storage facilities which are partially rehabilitated to be a health and socio-economic threat. Since 2013, when a close Gold Mining Company was liquidated, this community has been complaining about dust fallout. To validate the claims made by the community, this study reports on the dust deposition impacts, and respiratory illnesses risk posed by wind-blown generated dust. The study conducts an air quality assessment using dispersion modelling of windblown dust. Surface material from the TSFs was sampled, analysed for silica and heavy metal content using X-ray fluorescence (XRF) and inductively coupled plasma- mass spectrometry (ICP-MS). This study finds dust fallout, PM10, high in silica and uranium content which could potentially pose health threats to the surrounding community. The study further shows that dust deposition is the highest in July-October, with TSF6 posing a nuisance while TSF1 being a potential health threat owing to its particle size distribution for the surrounding gold mine village community. Potential receptors of the air pollution by dust in this study area include neighbouring property owners, business owners of the nearby shopping centre, the school and the clinic. This study further finds that sudden mine closure due to mine liquidation results in unrehabilitated tailings storage facilities which exacerbates dust deposition.

**Key words:** TSFs, windblown dust, respiratory illnesses, community, heavy metals, PM10.

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## INTRODUCTION

Though South Africa has guidance for the management of dust deposition through the SANS 1929 dust-fall guideline and the National Dust Control Regulation 2013, problems associated with dust deposition persist. The fact that the country has such standards should have hypothetically solved any dust deposition problems South Africa might have had (Martins, 2014). Deposition dust is the primary particulate material defined by Pöschl as material which can either be emitted as liquids or solids from natural sources: biogenic materials ( pollens, spores, micro-organisms, insects and needle-shaped particles), volcanic eruptions, biomass burning, sea salt, mineral dust and soil or anthropogenic sources: incomplete combustion of fossil/biofuel, wind-driven or traffic-related suspension of roads (Pöschl, 2005).

Windblown deposited dust is often a major nuisance problem faced in South African urban and peri-urban areas due to the prevailing dry climatic conditions, extensive surface mining and mineral processing (Held et al., 1996). This dust often results in air pollution, the National

Environmental Management Air Quality Act (NEM: AQA, 39 of 2004) defines air pollution as any change in the composition of the air caused by smoke, soot, dust (including fly ash), cinders, solid particles of any kind, gases, fumes, aerosols and odorous substances. This definition is similar to that of the World Health Organisation (WHO), which defines air pollution as a contamination of the indoor or outdoor environment by any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere (World Health Organization, 2016).

Gold-mining waste has been estimated as accounting for 221 million tons or 47 % of all mineral waste produced in South Africa, making it the largest single source of waste and pollution (Department of Water Affairs [DWAF], 2001). There are approximately 270 tailings storage facilities in the Witwatersrand Basin, covering 400 $km^2$ in surface area, which stores this waste (AngloGold Ashanti, 2004a). Tailings storage facilities (TSFs) are residue of the milling process used to extract valuable mined ores. Moreno et al. (2010) define tailings as the crushed, sand-like by-product refuse material which is generated during extraction, crushing, grinding and milling procedures of mined ore during the mining process. Emissions generated from mining activities are often associated with particulates, such as $PM_{10}$, $PM_{2.5}$ and dust fallout.

A number of TSFs are unlined and unrehabilitated, posing an environmental challenge, including water contamination by acid mine drainage (AMD), air pollution by windblown dust as well as particulate emissions (Maseki et al., 2017). In 2013, the West Rand District Environmental Management Framework estimated approximately 21.21 ton/day particulate emissions from TSFs in the Merafong Municipality, the largest emitter in the West Witwatersrand Basin (Gauteng Department of Agriculture and Rural Development, 2009). These impacts also include physical and aesthetic modification of the environment and challenges with sustainable vegetation cover as a result of soil contamination, since tailings contain toxic heavy metals.

Tailings storage facilities in the Witwatersrand area have, for many years, been a major source of air pollution due to fugitive dust emissions. Fugitive dust emissions from TSFs are believed to affect the quality of life, health and well-being of neighbouring communities, though no concrete evidence of this has been shown. In the Witwatersrand, dust fallout remains a prominent environmental hazar dduring the spring season, where wind erodible particulate matter ($PM_{10}$) concentrations can reach up to 2000 μg/$m^3$ (Annegarn et al., 2002; Annegarn et al., 1990; Blight and Caldwell, 1984; Ojelede et al., 2012; Oguntoke et al., 2013). According to Kneen et al. (2015), mining, tailings storage facilities, dust pollution and growth in residential housing development are synonymous with the Witwatersrand Basin.

A study by Oelofse et al. (2014) notes that mine closure and an increase in AMD has critical consequences for mining-affected communities. This view is supported by Adler and Rascher (2007), Warhurst and Norhona (2000), Claassen (2006) and Ojelede et al. (2012). At the time of these studies, sudden/ premature mine closure was uncommon. As a result, even to date, there are very few impact assessments studies linking sudden mine closure with dust deposition to environmental impacts and socio-economic impacts. Most studies look at one aspect of the problem. The present study is the first of its kind to look at sudden mine closure (due to mine liquidation), linking it with dust deposition and its environmental as well as socio-economic impacts. Sudden mine closure occurs when a mine closes before its scheduled period (International Council of Mining and Metallurgy, 2019). A gold mine in the West Witwatersrand was liquidated in the year 2013; due to confidentiality agreements the name of the mining company will not be mentioned in this study. It is the perception of the surrounding community in this mine area that the unrehabilitated TSFs are responsible for air pollution by dust deposition.

The purpose of this study was to conduct an air quality impact assessment on the surrounding community of the gold mining village found in the West Witwatersrand Basin. This paper investigates whether the community's perceptions about the dust emanating from TSFs are valid and seeks to recommend possible solutions to address the dust problem. The study draws special attention to TSF 6 which is the tailings storage facility which the community has mostly complained about.

The focus of this study is to identify and critically assess the impacts for dust deposition during the period of mine liquidation within a gold-mining village. To achieve this research aim, the following research objectives are addressed:

- To simulate the dust deposited from the surrounding tailings storage facilities in the vicinity of TSF 6 and the gold mining village using the AERMOD dispersion model.
- To conduct a chemical analysis of all TSFs material surrounding the gold mining village, to investigate the impacts, potential toxicity and health threats that it poses.
- To conduct a particle size distribution analysis to investigate the health threats posed by the dust size fraction.

## BACKGROUND

Previous studies confirm that tailings dust in the Witwatersrand region is associated with increased hospital admissions, emergency room visits, cardiovascular diseases, increased mortality and respiratory ailments (Friedrich, 2009; McKenna Neumann et al., 2009). The occurrence of heavy metals in small size fraction is also reported to be prevalent in the area (Lammel et al., 2006;

**Figure 1:** A windy day in the gold mine village.

Espinosa et al., 2001; Szakova et al., 2005; Kneen et al., 2015). Size fraction less than 10-75 µm can be eroded by the wind and blown into the surroundings.

Particle size is significant in terms of health effects since it controls where in the respiratory system a given particle is deposited. Fine particles are considered more hazardous than coarse particles as larger particles are less respirable and do not penetrate deep into the lungs (Manahan, 1991). Studies suggest that short-term exposure to particulate matter even at low concentrations (10 $\mu g/m^3$) of exposure is associated with negative health effects. Long-term exposure to low concentrations of particulate matter is associated with mortality and other chronic effects such as bronchitis and reduced lung function (WHO, 2002). The WHO (2006) reports that there is no safe threshold level of particulate matter exposure for human health.

Naicker et al. (2003), Bright (2007) and the American Thoracic Society (ATS) (1997) argue that exposure to respirable mine dust that contains silica poses health hazards to people living in close proximity of TSFs (< 500 m). Furthermore, occupational morbidity associated with human exposure to radiation or use of contaminated water sources within a mine is the major cause of noticeable mortality among miners. The decay of uranium to numerous gases found in TSFs provides a constant supply and source of radiation. Mining communities encroaching gold and uranium TSFs are exposed most to radiation. Radiation is also known to affect fertility and post-natal viability.

The WHO (1999) states that exposure to unhealthy environmental conditions contributes to 25% of ill health, particularly acute respiratory diseases such as asthma, bronchitis and tuberculosis. In 2005, it is estimated that globally, four million people died from chronic respiratory diseases (WHO, 2006). Studies by the AEA Technology (2005) mention that human health-related costs due to air pollution account for 80-94% of total external cost. In Greece, it is estimated that the external cost of PM10 emissions ranges between €3.6-14.1 million per year, based on damages to human health (Roussos-Ross et al., 2014).

This study investigates whether the dust from TSF 6 and surrounding TSFs poses air pollution threats in a gold mining village community in the West Witwatersrand Basin from a study conducted by Mpanza and Moolla in 2018. This study uses dispersion modeling to verify the validity of opinions about the threats posed by dust deposition from the TSFs in area. It appears that despite some studies being conducted on community complaints about unrehabilitated TSFs, a lack of support for communities through science persists when communities initiate litigation against a mining company. There is no convergence and integration between indigenous knowledge and factual evidence through science. This study attempts to bridge the gap between lay knowledge and science as well as demonstrating the interaction between a liquidated mine, the natural environment and the society in which the mine is located.

## STUDY AREA

Since the sudden mine closure occurred in 2013 due to a gold mining company being liquidated, the surrounding community has been complaining about dust. The gold mine village community, including the surrounding business owners, school and clinic, specifically complain during the windy season (August to October). In a study conducted in 2018 by Mpanza and Moolla (2019), the community stated that the dust triggers respiratory illnesses and community membersare thus required to spend money to treat these illnesses. Hence, this study, assesses the dust deposition impacts emanating from Tailings Storage Facility 6 and the surrounding tailings dumps. Figure 1 shows a windy day in the gold mine village, as observed by the surrounding affected community with dust emanating from TSF6.

The study area is classified as an urban environment located 6 km South West of Carletonville town. It involves all areas in the vicinity of TSF6, TSF1, TSF7, Dormant AGA, Doornfontein 1, Doornfontein 2, Savuka 5 and Savuka 7. The surrounding receptor communities include the gold

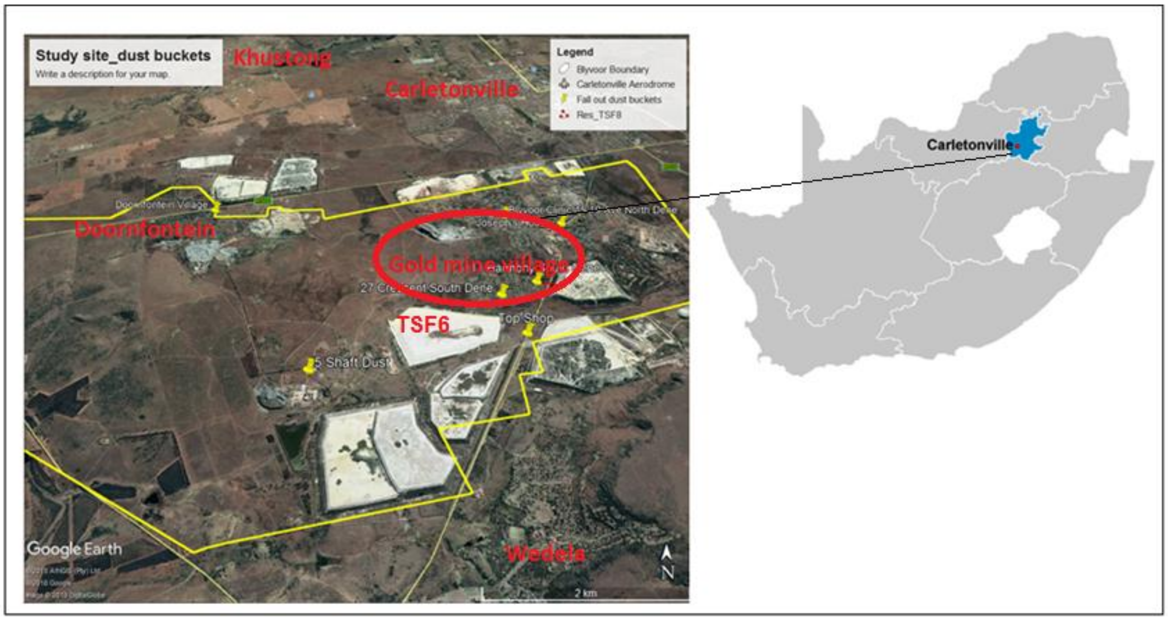



**Figure 2:** Study site with all TSFs in the vicinity of the gold mine village community.

mine village ward 5 and ward 27, Doornfontein mine village, Wedela, Fochville, Carletonville and Khutsong. The Merafong Municipality which hosts the study site of this study is estimated to have approximately 23 TSFs (Chevrel et al., 2008). Figure 2 shows the tailings storage facilities assessed in this study.

## METHODOLOGY

Various factors contribute to the dispersion, transformation and eventual removal of particles, from the atmosphere and the ground. Such factors include local meteorology, topography, land-use, source features (e.g. point, area, volume, line or pit source and source dimensions) and source strengths. A typical air quality assessment involves the assessment of measured ambient air quality data or dispersion modelling results. These are useful tools which evaluate the current state of air at a location, assessing air pollution and its sources at a number of locations. Total Suspended Solids (TSP) and PM10 are particulate matter investigated in this study as pollutants of concern. TSP and PM10 are investigated since they are particularly associated with mining activities. The US Environmental Protection Agency (USEPA, 1998) states that approximately 50% of the TSP is emitted as PM10, especially from mining sources.

The dispersion modelling conducted in this study is guided by the South African Regulations Regarding Air Dispersion Modelling (2014). Reference to the British Columbia Air Quality Dispersion Modelling Guideline (2015) and the Good Practice Guide for Atmospheric Dispersion Modelling, New Zealand (2004) is used as best practice in the impact assessment. This study firstly, considers emissions inventory for West Witwatersrand area, and reviewed the regulatory requirements and health thresholds for identified key pollutants. Dispersion modelling is conducted to determine the impacts on the receiving environment in the vicinity of the gold mine village and a screening assessment is carried out to determine compliance with the National Ambient Air Quality Standards (NAAQSs) and Dust Fall Control Regulations (NDCR).

The focus of this assessment was on the wind erodible sources, primarily the tailings storage facilities which, over time, have been partially vegetated. Other sources, such as the main mining roads and rock dump, have not been included together with other sources such as crushing and screening and plant emissions. The main mining road is tarred and at the time this study was conducted, there was no active mining. Waste rock dumps next to TSF1 were not included as sources of windblown dust since they contribute negligible particulate emissions. The vegetated portions of the TSFs were excluded from the assessment. The assumption is, negligible wind erosion occurs on the vegetated areas. A source apportionment was conducted on Google Earth by digitising the various TSFs to obtain the surface area. Figure 3 shows the methodology and processes followed in data collection and data analysis of this study.

To assess the effects of dust deposition and its impacts on the gold mine village community, the AERMOD dispersion model is used. The AERMOD (AERMOD Version 09292) was selected since it is a recommended model for sophisticated, near-source applications in all terrain types (where near-source is defined as less than 50 km from source). AERMOD

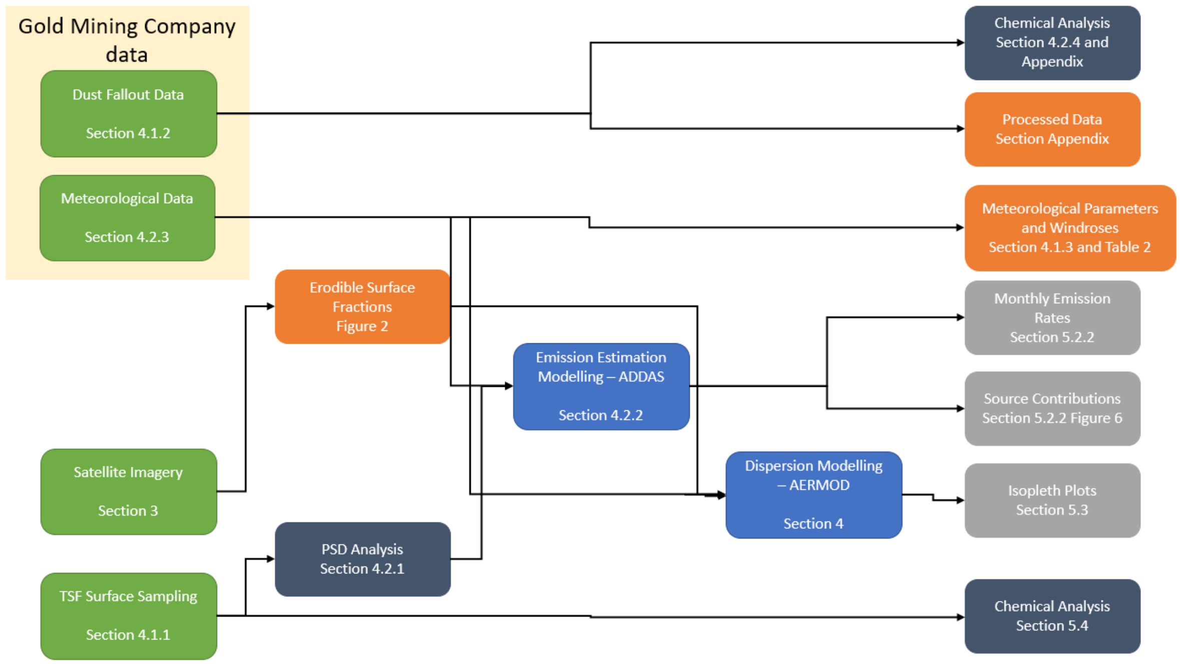



**Figure 3:** Process flow of the study methods.

models the TSFs as an area source. The community is located less than 100 m away from TSF 6 and 200 m away from TSF 7 which is far below the buffer distance recommended by the Chamber of Mines Guideline of 500 m. The model commonly applied to Level 2 assessments; the gold mine village case is classified as a Level 2 assessment (Regulation for Air Dispersion Modelling, 2014). Apart from the gold mine village, other communities which might be affected by dust from surrounding TSFs include Carletonville town, Khutsong South and Wedela, located within a 50 km radius from the centre of TSF 6 (Figure 2). AERMOD is a Gaussian-plume type dispersion model which assumes a steady state meteorology and a fairly flat topography. The input parameters include, source data, meteorological data (pre-processed by AERMET model), terrain data and data on the nature of receptor grid. AERMOD has a range uncertainty of -50% to 200%; the accuracy improves with fairly strong wind speeds and neutral atmospheric conditions. The uncertainty comes as a result of modelling the physics, input errors and stochastic processes.

## Data collection

### *Source material data: Surface sampling*

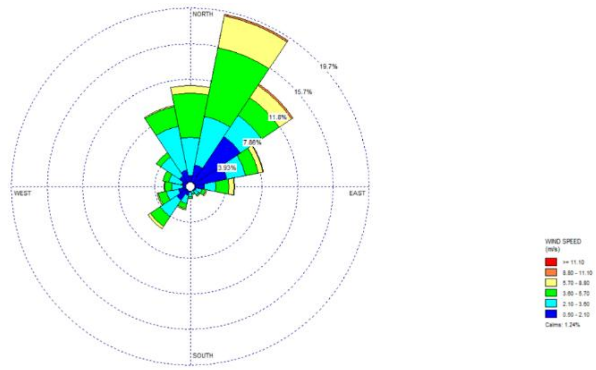
Material samples were selected from eight TSFs. The samples were chosen due to their proximity to the community of interest (gold mine village). The TSFs assessed include Dormant AngloGold Ashanti, TSF1, TSF6, TSF7, Savuka 7, Savuka 5, Doornfontein 1, and Doornfontein 2. The selection of tailings included all TSFs which occur within a 10 km radius from the gold mine village. The village is shown within a red circle in Figure 2, and consists of ward 5 and ward 27.

The samples were scooped from the top centre surface, crest and slope surface of each tailings dam on all side of the tailings. This material was mixed in one sample bag as one representative sample for each of the ten tailings storage facilities (a total 10 representative samples were analysed). Material from the top centre of the TSF represents the core deposited material as original material. Side slope material represents material eroded from the top layer by wind and water. Chemical analysis and particle size distribution was conducted on this sample data. The particle size analysis from the surface material defines surface roughness, together with moisture content, clay content, silt content, particle density and bulk density, which are required inputs in the ADDAS model.

### *Monitoring data: Dust fallout sampling*

The sampling of dust fallout was conducted in all the areas marked in yellow (Figure 2). Samples were collected from the dust fallout monitoring campaign which uses a method called the American Society for Testing and Materials Standard Method for Collection and Analysis of Dustfall (ASTM-1739). This single dust bucket collects dust fallout, PM10 and PM2.5 particulate as it lands in the bucket. The dust data was collected to validate the dispersion modelling

**Table 2:** Meteorological parameters from the WW Mponeng plant station.

| Parameter Period from January 2012 to December 2017 | | Wind Rose Diagram |
|---|---|---|
| Wind Direction | N; NE |  |
| Wind Speed | 2.94 m/s | |
| Precipitation | 67 mm | |
| Relative Humidity | 54%-71% | |
| Atmospheric Stability | Fairly neutral | |
| Solar Radiation | 283 | |
| Receptor Grid | 7.5 km × 7.5 km | |
| Temperature | 10-23$^0$C | |

results and to assessthe particle sizes and chemical content of the actual dust particles. At the AngloGold Ashanti meteorological station (Mponeng Plant Station), meteorological data, dust fallout and PM10 have been monitored since 2012 using an airborne sampler. The data were supplied for this study. For each tailings dam, three dust samples were collected for chemical analysis and particle size distribution analysis. Each of these samples represented the duration of the windy season in 2018, from August to October (see appendix). The results of the dust monitoring data are presented in Section 5 and are used in model validation process.

### *Meteorological data*

Meteorological characteristics affect the rate of emissions from fugitive dust sources and govern the dispersion potential and eventual removal of pollutants from the atmosphere (Pasquill and Smith, 1983). To characterise the meteorological setting of the area, data from AngloGold Ashanti meteorological station (Mponeng Plant Station) were used, consisting of wind speed, precipitation, relative humidity and wind direction (Table 2). The data covered the period of mine liquidation, which began in 2012 and continued till 2017. The year 2012 marks the year just before the gold mining company was placed under liquidation in 2013. Hourly data of the aforementioned period were obtained and input files were generated using the AIRMET pre-processor for the dispersion simulations.

## Data analysis

### *Particle size distribution*

To characterise each TSF, the particle size distribution, moisture content, clay content, silt content, particle density and bulk density were analysed as agents of particle entrainment, transport and deposition from the surface material. The particle size distribution was undertaken on the surface material using the Malvern Master Sizer system. Particle aerodynamic diameters determine if and for how long dust remains airborne, its likelihood of being inhaled and its site of deposition in the respiratory system.

### *Emissions quantification*

Input files were prepared according to Marticorena and Bergametti (1995) model as part the windblown dust emissions quantification in the study area. The Marticorena and Bergametti (1995) model accounts for variability in source erodibility by parameterising the erosion threshold (based on particle size distribution of the source) and roughness length of the surface material. The model also takes into account soil crusting related to friction velocity, these control the horizontal and vertical movements of dust. The emission rates were determined using the Airborne Dust Dispersion model from Area Sources (ADDAS) from the entire study site. This is an Airshed Planning Professionals' in-house model (Burger, 2010). The ADDAS model uses the threshold friction velocity of the particle size and the vertically integrated horizontal dust flux (see Equations 1, 2 and 3) based on the Marticorena and Bergametti (1995) model (Burger, 2010):

$$E_i = G_i 10^{(0.134C-6)} \quad (1)$$

$$G_i = 0.261\frac{\rho_a}{g}U_{i+1}^3(1+R_i)(1-R_i) \quad (2)$$

$$R_i = \frac{U_{i+1}}{U} \quad (3)$$

Where $Ei$ = emissions rate (size catergory); $C$ = clay content (%); $\rho_a$=air density; $Gi$ = gravitational acceleration, $U$ =

**Table 1:** ADDAS model key inputs for dispersion modelling, moisture content and surface cover.

| Location | Density ($kg/m^3$) | Moisture (%) | Surface Cover (%) | Undisturbed-non-vegetation (Y/N) | Min U*t | Erodible Fraction (%) |
|---|---|---|---|---|---|---|
| TSF7 | 2640 | 0.69 | 48 | N | 5.4 | 52 |
| TSF6 | 2640 | 0.09 | 10 | Y | 5.4 | 90 |
| SAVUKA 5 | 2640 | 4.14 | 19 | N | 5.4 | 211 |
| SAVUKA7 | 2640 | 0.48 | 27 | N | 5.4 | 57.01 |
| DORMANT AGA | 2000 | 0.07 | 87 | N | 5.4 | 81 |
| TSF1 | 2000 | 0.04 | 20 | Y | 5.4 | 211 |
| DOORFONTEIN 1 | 2000 | 0.07 | 90 | N | 5.4 | 19.75 |
| DOORFONTEIN 2 | 2000 | 0.08 | 1 | N | 5.4 | 73 |

frictional velocity; and $U_{i+1}$= threshold friction velocity (size category 1).

The ADDAS Model key inputs are summarised in Table 1. To cover the entire study area (as shown in Figure 2) a 7.5 km by 7.5 km receptor grid with a 100 m resolution was used for dispersion modelling purposes. According to the Greek National Pollutant Inventory [NPi] (2012), an emission factor of 0.4 kg/ha/h should be adopted for TSP while a factor of 0.2 kg/ha/h should be used for PM10. These emission factor values are supported by Environment Australia (2001). The values were used as part of data validation, improving certainty in the modelling process. The US EPA finds that the friction velocity of 5.4 m/s initiates erosion of coal from a storage pile; this was used as a guide in this study (US EPA, 2006). Milan and Yanful (2003) calculated a wind speed of 9 m/s as the speed required to initiate erosion from tailings storage facilities in New Brunswick and Ontario, Canada. Table 1 summarises all the data inputs for the ADDAS model.

The TSFs were considered to be inactive as no active mining was taking place in the study area at the time of data collection. The surface roughness length was considered to be the same for all tailings as the TSFs possess similar characteristics.

### *Meteorological data analysis*

The meteorological data were analysed through wind rose diagrams illustrating wind direction and wind speed (see results in Table 2). The meteorological data were used as input in the ADDAS model to determine the atmospheric dispersion potential in the study area.

### *Chemical analysis*

To characterise contaminants within the selected TSFs, chemical analysis was conducted for all soil samples and dust samples collected in the area. The analysis included XRF and ICP-MS analysis. The ICP-MS analysis indicates the toxic metals which have potential to affect human health. The ICP-MS analysis followed the USEPA 3051a procedure. The X-Ray Fluorescence (XRF) analysis was also undertaken. This is a non-destructive technique used to determine elemental composition of the sampled material.

### Model validation

All measured dust fallout data were used to compare with the dispersion simulations (see Table 3 in the appendix).

### *Limitations and assumptions*

The simulations only include emissions associated and in close proximity of the gold mine village ward 5 and ward 27. The vegetated area and rock dumps were excluded from the assessment as they were assumed not to contribute to the windblown dust. The study relied on aerial photographs of the area as part of source data characterisation. The TSFs were the only source considered in the modelling process. The AERMOD model is not a good estimator of near source impacts and the community is located 60 m away from TSF6 and 100 m from TSF7.

## RESULTS AND DISCUSSION

### *Meteorological parameters*

The extent to which pollution accumulated or dispersed in the atmosphere (atmospheric dispersion potential) depends on meteorological factors such as wind speed, wind direction, air temperature etc. The wind speed determines the distance of downwind transport and the rate of dilution as a result of plume stretching (Liebenberg-Enslin, 2012). The wind speed governs the mechanical turbulence affected by surface roughness. Wind direction determines the pathway that the pollutants will follow and the spread of the winds (Shaw and Munn, 1976; Pasquil and Smith, 1983; Oke, 1990). Air temperature determines plume buoyancy, mixing and inversion layers. Rainfall represents the removal of pollutants from the atmosphere. Atmospheric stability determines the heating of the ground and mechanical mixing due to the friction effects from the earth's surface. Table 2 of the appendix summarises the meteorological parameters obtained from the WW

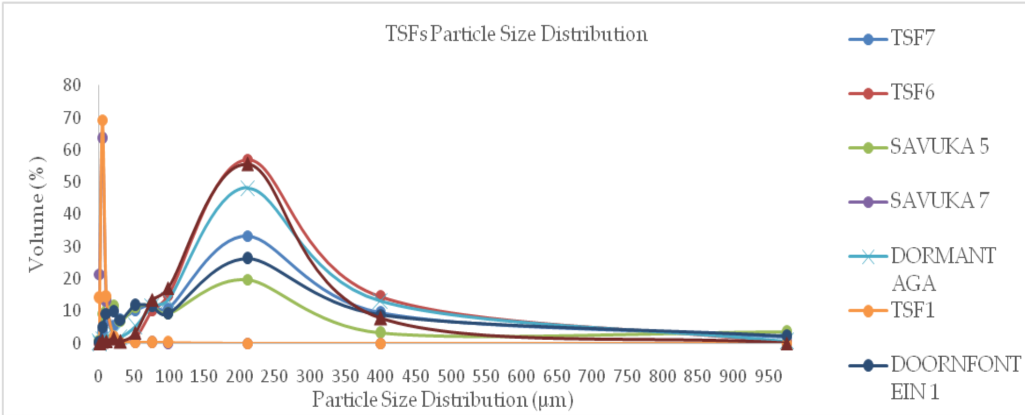



**Figure 4:** Particle size distribution for study site tailings storage facilities.

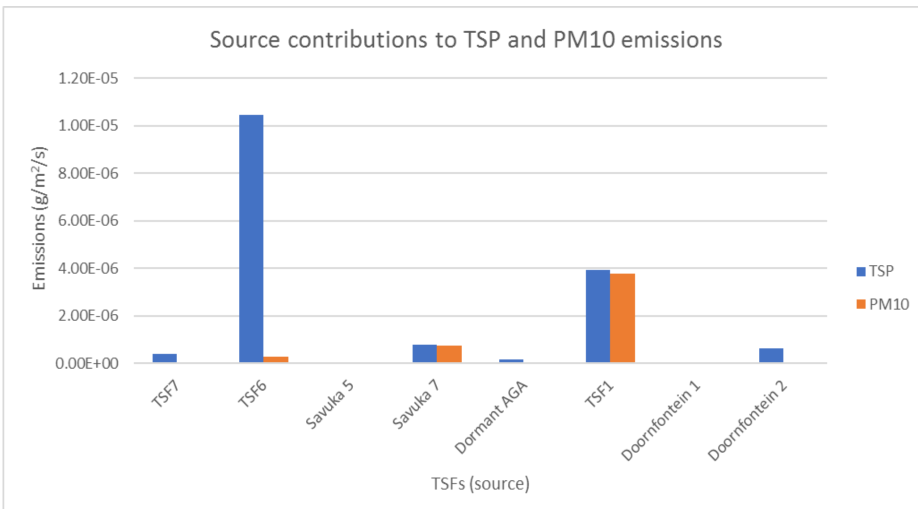



**Figure 5:** Source contribution to overall emission rates TSP and PM10.

Mponeng Plant Station.

The wind rose in Table 2 shows an average wind speed of 2.94 m/s. The wind rose has 16 spokes, which illustrate the direction in which the wind blew at specific periods. The colours used in the wind rose, reflect the different categories of wind speeds, for example, dark blue shows a range of 0.5 to 2.10 m/s, and light blue shows a range of 2.10 to 3.4 m/s. The strongest wind speeds are greater than 6 m/s, which occurred mostly during the spring months. The USEPA (2006) suggests that a wind speed threshold of 5.4 m/s is typical for tailings storage facilities to initiate wind erosion. The general wind direction in the study area is Northerly and North-Easterly. July to August represents the driest months, with low precipitation. This allows wind erosion to occur with ease. The average rainfall during the liquidation period was 67 mm. The study area has neutral atmospheric conditions in general (West Wits Air Quality Assessment, 2014).The wind speed assisted in calculating the friction velocity required by the ADDAS model.

## Dust emission rates

### *Particle size distribution*

As shown in Figure 4, TSF1 has the bulk (97%) of its particle size distribution ranging between < 2 and 30 µm (fine material), followed by Savuka 7. From the graph, it is evident that TSF6 and Doornfontein 2 have primarily coarse material, while TSF7, Savuka 5, Dormant AGA and Doornfontein 1 show a mix of both fine and coarse material. It is expected that TSF1 will show high contributions of PM10 while TSF6 will show the highest dust fallout and TSP emissions (see Figure 5). TSF1 and Savuka 7 are the biggest health threats, owing to its high respirable fraction of particulate matter. These two TSFs surround the gold mine village, although TSF 1 is located 800 m away from the first line of houses in the gold mine village.

Tegen and Fung (1994) state that global dust emissions consist of 13% of particle size ranging from 0.5 to 1 µm,

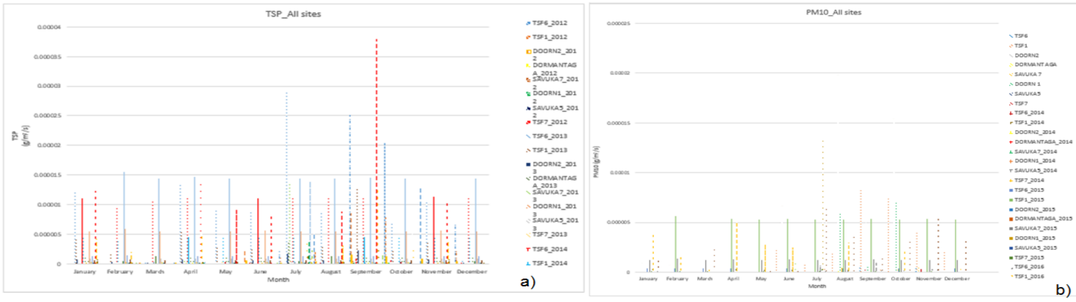



**Figure 6:** Seasonal emission rates a) TSP and b) PM10.

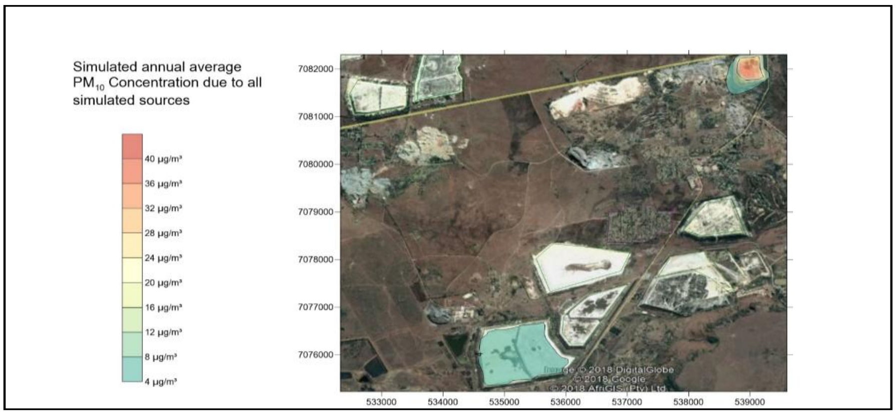



**Figure 7:** Simulated annual average PM10 concentration due to all simulated sources.

while 65% in the range of 1 to 35 µm and 22% in the range of 35 to 50 µm. In this study, approximately 60% of the particle size was between 2-40 µm. From the size analysis, it is clear that the community in the gold mine village is affected by PM10 and dust fall owing to its location close to TSF1 and TSF6. Fine particulate matter is known to induce subtle health effects, mostly respiratory diseases and physiological potency (Espinosa et al., 2001; Paschoa et al., 1984).

It appears that TSF1 underwent hyperfine milling of ore during reprocessing and this resulted in fine material. TSF 6 has mainly coarse particle sizes; this storage facility has not been reprocessed to date. For the community close to the gold mine, TSF6 contributes nuisance dust (inhalable dust) covering a distance of 60-1000 m which triggers community complaints, while TSF1 consists mainly of the respirable dust fractions.

### *PM 10 and TSP emission rates*

The PM10 and TSP (in g/m²/s) average emission rates at the selected TSFs are shown in Figure 5.

TSF 6 contributes the highest emissions and has the largest surface area (1086773 m²) while TSF1 contributes the highest PM10 emissions, as shown in Figure 5. This is no surprise as this TSF showed the highest percentage of particle size distribution in the <2-30 µm range and is partially vegetated.

Figure 6a and b summarises the seasonal variation effect on TSP and PM10 emission rates over the different sources.

During the spring season (August-October), the highest emission rates were calculated for TSP in TSF6 in 2012, 2013 and 2016. In all these years, the gold mining company in close proximity to the community was under the supervision of the liquidator. Similarly, for PM10 the highest emission rates were reached during the windy season (July-October). The highest PM10 rates were calculated at TSF1 in 2014 and 2016; and at Savuka 7 in 2016. The better vegetated TSFs such as Savuka 5, Dormant AGA and TSF7 showed the least emission rates. This reinforces the premise that rehabilitated TSFs are less of an environmental and human health threat.

### Dispersion simulations

The model simulation results are the ground level concentrations (GLCs) in µg/m³ for PM10 and dust deposition rate in mg/m²/day for dust fall and TSP. The results are shown as graphical presentations of isopleths shown from Figures 7 to 10. The isopleth plots depict

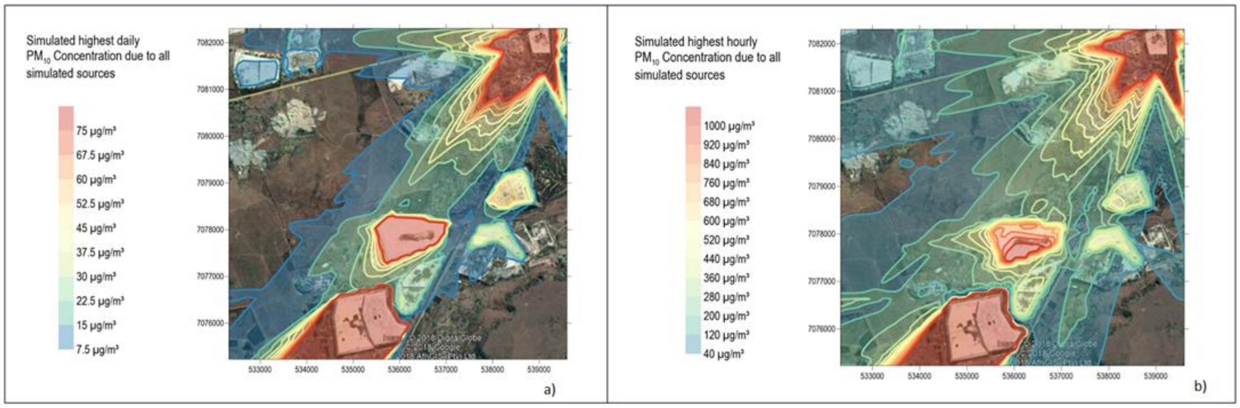



**Figure 8:** Simulated highest daily PM10 a) and highest hourly PM10 b) concentration due to all simulated sources.

interpolated values from the concentrations simulated by AERMOD for each identified receptor point. The hourly, daily, monthly and annual averages are shown for worst cases and these were compared with the NAAQS and NDCR as shown in the appendices.

### *$PM_{10}$ simulations*

The modelled annual average $PM_{10}$, ground level concentrations due to wind erosion from the TSFs are presented in Figure 7. No clear exceedance of South African air quality standard of 40 µg/m³ annual average is evident. In TSF1, located 800 m from the first line of houses in the gold mine village, PM10 GLCs reach up to 32 µg/m³ annual average which is within the standard. The isopleths show a very limited impact which covers a 100 m radius from the centre of TSF 1. The gold mine village is located on the downwind side of TSF1, which means that it is potentially affected by this tailings dump at very high wind speeds in the short term. Figure 8 summarises the simulated highest daily PM10 and the highest hourly PM10

TSF 6 and TSF 1 seem to be directly impacting the community with no clear exceedances of the 75 µg/m³ daily air quality standard. Figure 8b summarises the highest hourly ground level concentrations of PM10 in the study area. It should be noted that there is a possibility that even though a high hourly average concentration is simulated at certain locations (TSF1, TSF6 and Savuka 7), this may have been a possibility for one or two hours at a time while the 24-h average concentrations may have remained in compliance with the standard. The community of Wedela (located south of Savuka 7) seems to be the most affected as it is located downwind of all the TSFs assessed in this study area. This community is outside of the study area thus not shown in Figure 8. There is a major threat of impacts in the short term which could be the source of the community's complaints on specific days and months. Although simulated concentrations appear to be below the daily standard, the short-term exposure is enough of a threat to trigger respiratory diseases. Several studies suggest that short-term exposure to particulate matter is associated with negative health effects, even at low concentrations of exposure (Pope and Dockery, 1992). Furthermore, short-term exposure to outdoor air pollution PM10 and PM2.5 can worsen respiratory symptoms. Pope and Dockery (1992) studied daily mortality in relation to $PM_{10}$ in Utah and found that daily average of 365 µg/m³ had recorded effects on mortality. Short-term exposure to PM10 is associated with lower respiratory symptoms, medication use and small reductions in lung function (Pope and Kanner, 1993). The community of this gold mine village made mention of having to buy medication to treat respiratory diseases during the windy season (Mpanza and Moolla 2019). Particulate matter is known to exacerbate asthma due to cellular oxidative stress, initiated by particle-produced free radicals. There is strong evidence suggesting that short-term increase in ambient concentrations of PM10is associated with increase in PM10 related morbidity (Quah and Boon, 2003).

It is an interesting finding to observe that the community perceives TSF 6 as a major health threat to them whereas this study shows that TSF6 consists of mainly nuisance dust. The gold mine village is situated on the downwind side of TSF1, while TSF6 poses a major nuisance to the Wedela community and the OK shopping centre on the downwind side of this TSF. This study suggests that when a mining operation is closed suddenly due to liquidation, poor rehabilitation of TSFs can generate dust posing health threats.

### *TSP and dust fall simulations*

Simulated highest hourly dust fallout and TSP are shown in Figure 9. The TSP has implications on dust fall as it is coarse-grained and is eventually deposited.

The simulated highest hourly dust fall and TSP dust deposition rates from all sources show high short-term dust fall which is equivalent to daily dust fall rates higher

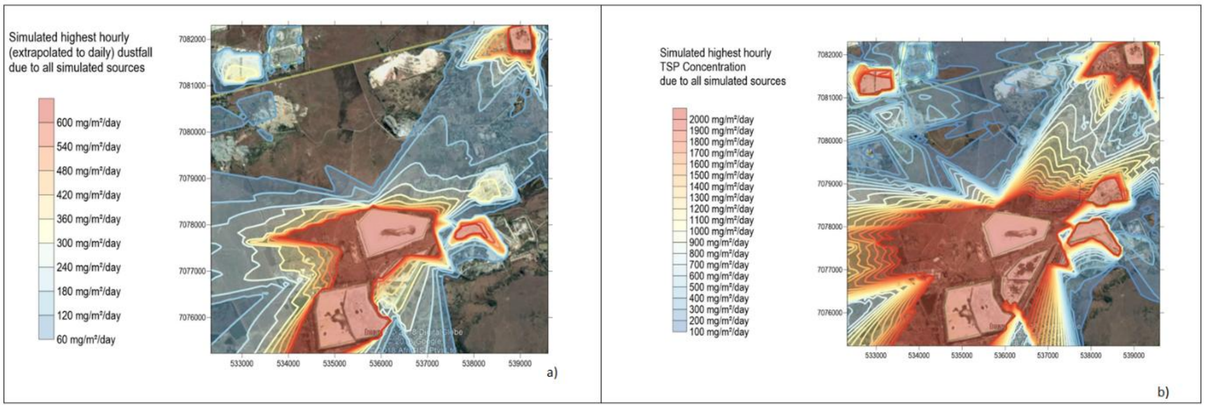



**Figure 9:** a) Simulated highest hourly Dustfall and b) TSP due to all simulated sources.

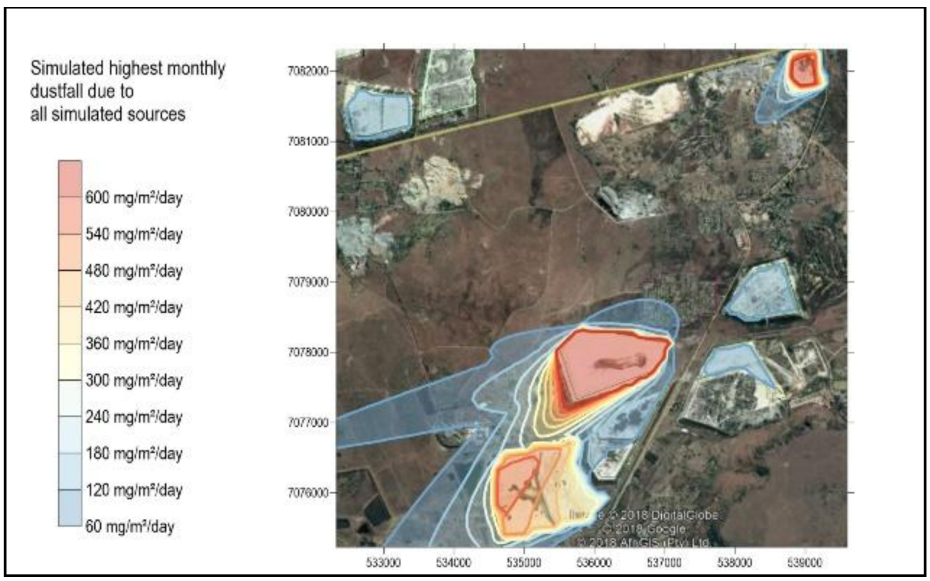



**Figure 10:** Simulated highest monthly dust fall due to all simulated sources.

than 600 mg/m$^2$/day. The highly affected receptors appear to be located away from the gold mine village to the South West (see Figure 9a and b, respectively). The highest simulated dust fallout rate is 600 mg/m$^2$/day, from TSF1, TSF6 and Savuka 7. The highest hourly dust fallout rates simulations are very high for both dust fallout and TSP. This is another indication of high exposure in the short term. During the entire study period in August, a total of 30 h (highest hours) were recorded of dust fallout, TSP and particulate matter at high wind speeds > 5.4 m/s (see Appendix) for the entire study period. Research reports that air pollution in cities of developing countries is responsible for some 50 million cases per year of chronic coughing in children younger than 14 years of age (Cohen et al., 2005). Chay and Greenstone (2005) found that higher concentrations of total suspended particulates (TSPs) are strongly associated with higher rates of infant mortality. Furthermore, maternal exposure to pollution also raises infant mortality.

The simulated highest monthly dust fall rates due to all simulated sources are shown in Figure 10.

There are exceedances of the NDCR with dust fall rates reaching 600 mg/m$^2$/day at TSF 1, TSF6 and Savuka 7. These exceedances, however, have no clear impact on the community of the gold mine village. The NDCR allows for two days non-sequential exceedances per year.

### *Simulated results and measured data*

Simulations and measured data were expected to differ, as simulations only included emissions associated with the TSFs in the vicinity of the gold mine village area as modelled. The sampled or measured dust fall rates include sources from areas close to the mine village (see Figure 2).

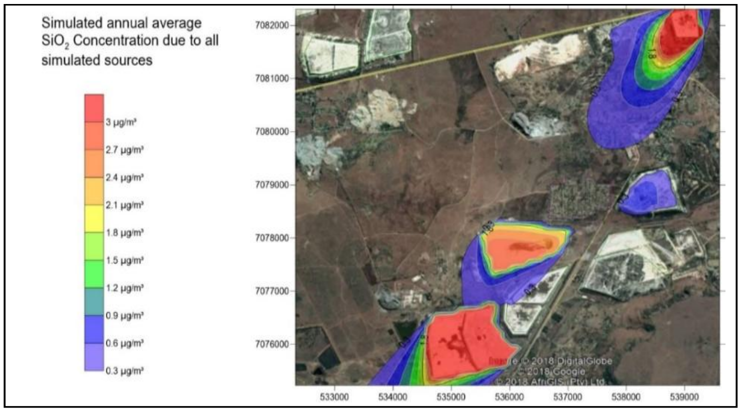



**Figure 11:** Simulated annual average $SiO_2$ concentration due to all simulated sources.

Table 1 in the appendix shows the measured and the simulated results. It is evident that simulated dust fall rates are less than the measured dust fall rates. This was expected due to the assumptions made and the modelling inputs. A major reason for a mismatch in the results could be that the parameters in the model are not readily amenable to reflect local factors, thus leading to discrepancies in outputs. The AERMOD model is originally set up for the United States of American environment and not the South African conditions.

## TSFs chemistry

The elemental investigation aimed to find out whether there was any silica content in the dust, which is a potential health threat to the surrounding communities. The study found that silica was the most abundant of all the other minerals in all the TSFs, ranging from 65- 93%. Other major elements included Al, K, Fe, Mg, and Mn in small quantities. The ICP-MS results indicated the presence of As, Pb, U, Cr, Ni, Cd, Au and Se. Makgae (2011) and Maseki (2013) observed that numerous mining residential areas are at risk of high silica and radioactivity contamination. This is due to the silica and uranium content found in the tailings storage facilities, especially in the Witwatersrand Basin.

To examine the potential health impacts that could be posed by the heavy metals, enrichment factors were calculated. According to Dudu et al. (2018), the enrichment factor (EF) method is one way of quantifying the anthropogenic pollution of a given site. The assumption made in calculating EF is that the ratio is 1 for elements not above crustal average. EF greater than 2 shows enriched elements above crustal average, meaning additional sources have contributed to the elemental composition. In this study, Au, U and As have a high enrichment factor, significantly above crustal average, ranging from 72-359, 30-82 and 33-317, respectively. TSF7, TSF6, TSF1 and Dormant AGA were assessed as they closely surround the gold mine village community.

The elemental content of the TSFs is a product of the ore and materials used in the gold treatment and extraction processes (Ersoy et al., 2004; Mendez and Maier, 2008). The major concerns, however, are silica and uranium, which are both carcinogenic at high levels over a period of time. These are known to pose respiratory diseases and cancer. This supports the community complaints and claims that the dust poses health threats and triggers respiratory diseases.

It is not surprising to see this trend as it was found by Maseki et al. (2017) that As, Pb, U and Au are highly enriched in the West Witwatersrand Basin. This is owing to the increased uranium and gold content of the Dominion Reef mined in the Basin. Studies conducted in the Witwatersrand Basin investigated airborne radioactivity levels through radiometric surveys and confirmed high doses of uranium in and around TSFs (Larkin et al., 2004).

A high silica content is also recorded from the TSFs. Acute exposure to high concentrations of silica can cause cough, shortness of breath and pulmonary alveolar lipoproteinosis (acute silicosis), provided it is fresh cut. After chronic but lower workplace exposure to silica for 6 to 16 years, the small airways become obstructed, as measured by pulmonary function tests.

The simulated annual average $SiO_2$ concentration due to all simulated sources is shown in Figure 11.The Californian Office of Environmental Health Hazard Assessment provides a chronic inhalation reference exposure level of 3 $\mu g/m^3$ for respirable crystalline silica. The simulated annual average of $SiO_2$ is shown to exceed 3 $\mu g/m^3$ at TSF 1, TSF 6 and Savuka 7. TSF1 presents a threat to the community at ward 5, as wind is blowing from this source 2km towards the community, however, it appears not to reach ward 27. TSF 6 and Savuka 7 have effects on the Wedela community as it is downwind of these tailings dumps.

According to the Mine Health and Safety Act, 1996, Section 11.6 mentions that if silica content in coal dust is greater than 5%, employers must establish and maintain a system of medical surveillance. Section 11.7 mentions that medical surveillance must be established and maintained for employees working in places in excess of 10% or 0.1 mg/m$^3$ Occupational Exposure Limit (OEL) for crystalline silica dust. Respirable crystalline silica is considered a great concern and a greater danger than ordinary dust (ATS, 1997; International Agency for Research on Cancer 1997; Shanklin and Smalley, 1998). Epidemiological studies have established correlations between respirable crystalline silica particulate matter with acute and chronic respiratory disorders, for example, chronic silicosis (Dockery and Pope, 1994; Hassanien et al., 2009; Rapant et al., 2006; Tursic et al., 2008). No silica exposure standards exist for the public; only occupational standards exist in South Africa.

Makgae (2011) and Maseki (2013) note that numerous mining residential areas are at risk of high radioactivity contamination. This is due the uranium content found in the tailings storage facilities, especially in the Witwatersrand Basin. To examine the potential health impacts that could be posed by the heavy metals shown in Table 3 in the Appendix, enrichment factors are calculated. Toxic metals such as As, Pb, U, Zn, Ni, Cr and Cd were considered when calculating enrichment factors. The equation for calculating the EF is as follows:

$$EF = \frac{M_x * Fe_b}{M_b * Fe_x} \quad \text{Equation 5}$$

Where $M_x$ and $Fe_x$ are the concentrations of element M and Fe in the sample $x$ and $M_b$ and $Fe_b$ are the mean concentrations of the element M and Fe in the continental crust (Wedepohl, 1995).

Iron is used as a reference element (43 200 ppm), as suggested by Taylor and McLennan (1995). In this study, Au, U and As have an extremely high enrichment factor, far greater than crustal average, ranging from 72-359; 30-82 and 33-317 respectively. Similar results were documented by Maseki et al. (2017) that Cd, Au and As have high enrichment factors, falling in the class of extremely high enrichment (EF> 40). Gold enrichment is not a great concern since it is biologically inert, therefore poses no potential harm to human health (Walker, 2007). Ohlander et al. (2007) explain the enrichment of metals (As and Cd) in pyrite rich tailings by adsorption to pyrite or iron-oxyhydroxides occurring with the oxidation of pyrite. The enrichment of Au and As has similarities with previous work in the Witwatersrand, where the association between As and Au was attested (Foya et al., 1999). According to Simon et al. (1999), the association between As and Au is justified by the fact that As plays a major role in enhancing the adsorption of gold complexes pyrite surfaces.

## CONCLUSION

The community provided perspectives on their daily experiences of the environment. The dispersion model provides the overall scientific evidence about the status of the environment with respect to air quality. In the 21st century, the integration of indigenous knowledge and science cannot be overlooked, especially to provide fast monitoring and management of the environment. The community perspectives were comparable to the dispersion simulations and the emission rate calculations. The dust emissions are prevalent during the windy season, with August-September being the highest months, as correctly pointed out by the community. The community, however, was inaccurate in saying that TSF6 is a major health threat. It is, in fact, a nuisance in the windy season. In the entire study period (2012-2017), only 35 h showed high wind speeds capable of transporting dust over large distances greater than 6 km. An analysis of the source material and dust samples showed the presence of particles in the thoracic and respirable range in certain TSFs, which are known to be more toxic once inhaled. In the short term, the modelled PM10 has potential to trigger respiratory diseases. Modelled PM showed that the daily PM10 concentrations at TSF6, TSF1 and Savuka 7 were slightly above the acceptable exposure limit. The results from the assessment showed that strong Northerlyand Easterly winds blowing to the South West are more frequent as compared with other wind patterns and lead to tailings dust deposition south of the TSFs. The chemical analysis showed that Au, U, and As were extremely highly enriched, with EF > 40. This is due to the geochemistry of the Witwatersrand Basin and mining processes. TSF 1 is a potential health threat in the long term while TSF6 is a nuisance in the short term. To show the potential effects of the dust to human health in the community of the gold mine village, a full health risk assessment should be conducted by a qualified toxicologist.

It is recommended that during the a sudden mine closure period due to mine liquidation, the Department of Mineral Resources and Energy exercise their authority to ensure that liquidators rehabilitate TSFs on behalf of a mining company. This can ensure management of TSFs while mitigating environmental and health impacts.

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## APPENDIX

**Table 3:** Predicted and measured dust fall out, highest monthly dust deposition at all receptors.


Figure1. Tailings sites

Table 1. National Dust Control Regulation

| RESTRICTION AREAS | DUST FALLOUT RATE (MG/M²/DAY, 30 DAYS AVERAGE) | PERMITTED FREQUENCY OF EXCEEDING DUST FALL RATE |
|---|---|---|
| Residential area | D < 600 | Two within a year, not sequential months |
| Non-residential area | 600 < D < 1200 | Two within a year, not sequential months |

Table 2.NAAQS Exposure limit PM10

| Source | Daily Average | Annual average |
|---|---|---|
| Initial NAAQS[a,b] | 120 μg/m³[d] | 50 μg/m³[e] |
| Current NAAQS [a,c] | 75 μg/m³[d] | 40 μg/m³[e] |
| WHO[f] | 50 μg/m | 20 μg/m |

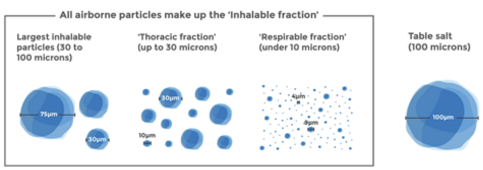



Figure2.: Particle size distribution impact

Table3. Predicted and Measured dust fallout, Highest Monthly dust deposition at all receptor

| Name | Distance from TSF6 | Highest Monthly Modelled Dustfall Rate | Highest Monthly Measured Dustfall Rate | Measured dust deposition levels annual average | South African Ambient Air Quality Standard (μg/m³) 2015 |
|---|---|---|---|---|---|
| | m | mg/m²/day | mg/m²/day | mg/m²/day | mg/m²/day |
| No. 5 Shaft | 1408 | 68 | 450 | 193 | Dust Monthly-Residential D < 600 mg/m²/day |
| 27 Crescent South Dene | 300 | 96 | 750 | 215 | Non Residential D < 1200 mg/m²/day |
| Doornfontein Village House | 3984 | 10 | 480 | 200 | |
| 1 Harmony South Dene | 866 | 23 | 490 | 168 | |
| Top Shop | 400 | 45 | 600 | 277 | |
| Joseph | 2500 | 14 | 540 | 190 | |
| Clinic | 2315 | 24 | 500 | 184 | |

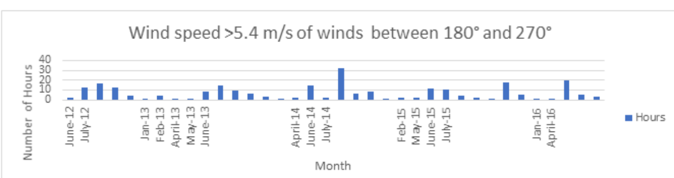



Figure3.Wind speed > 5.4 m/s

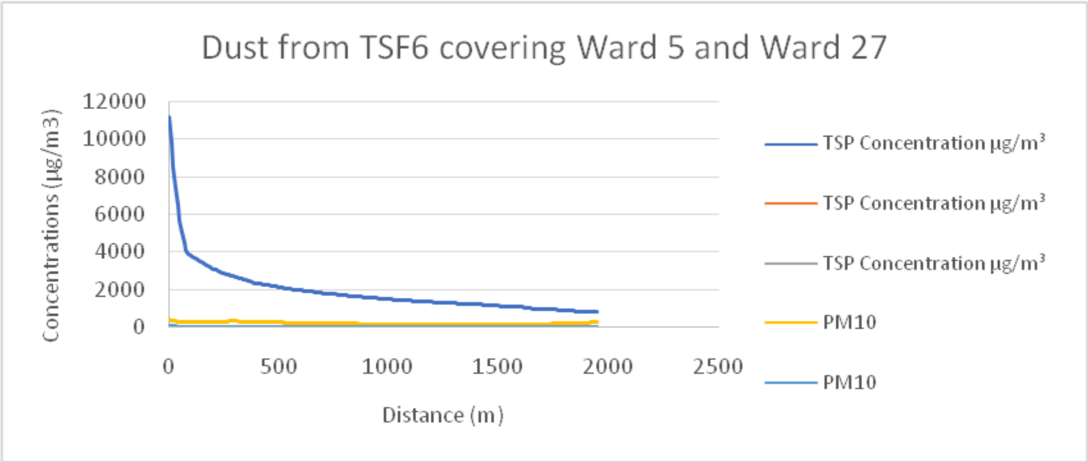


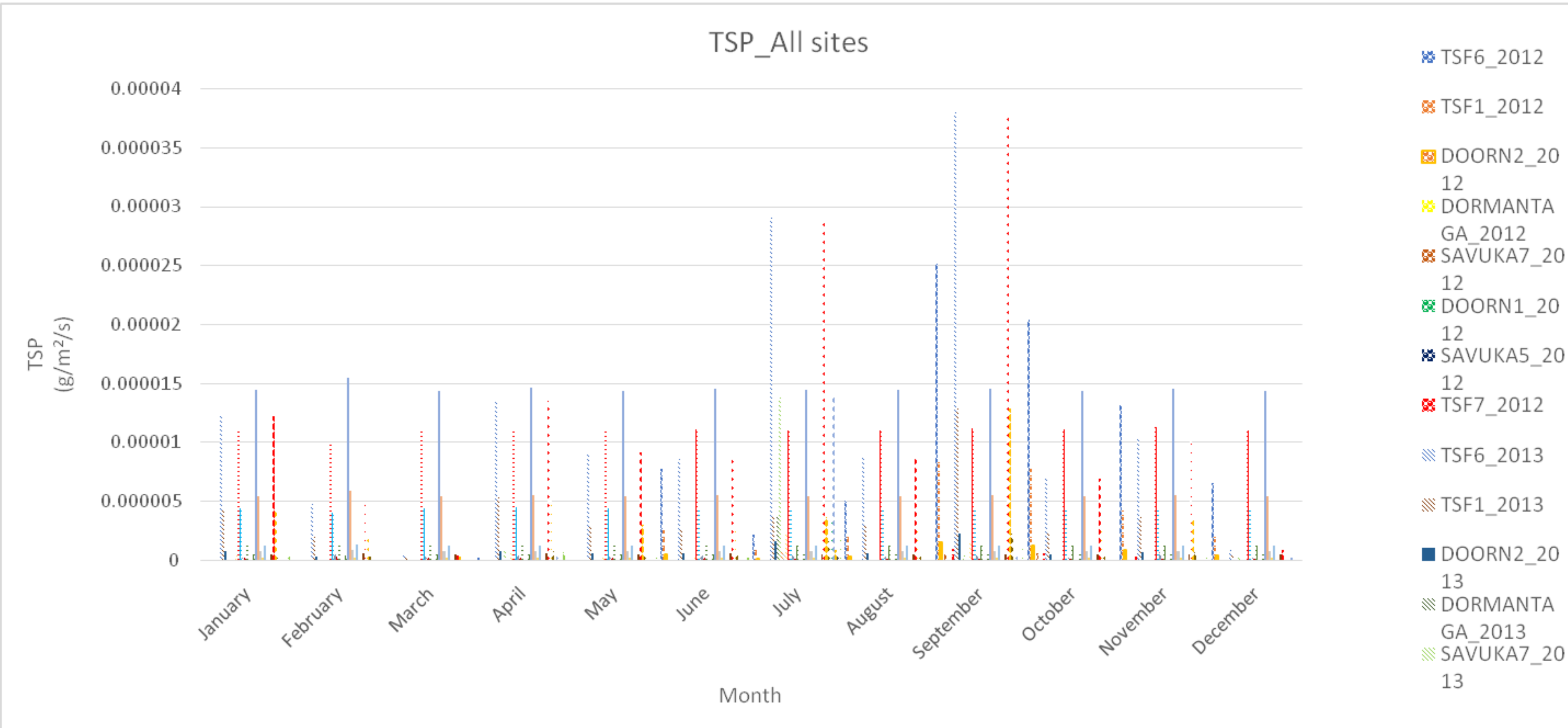

**Figure 1:** Distance covered by dust in ward 5 and 27 from TSF6.

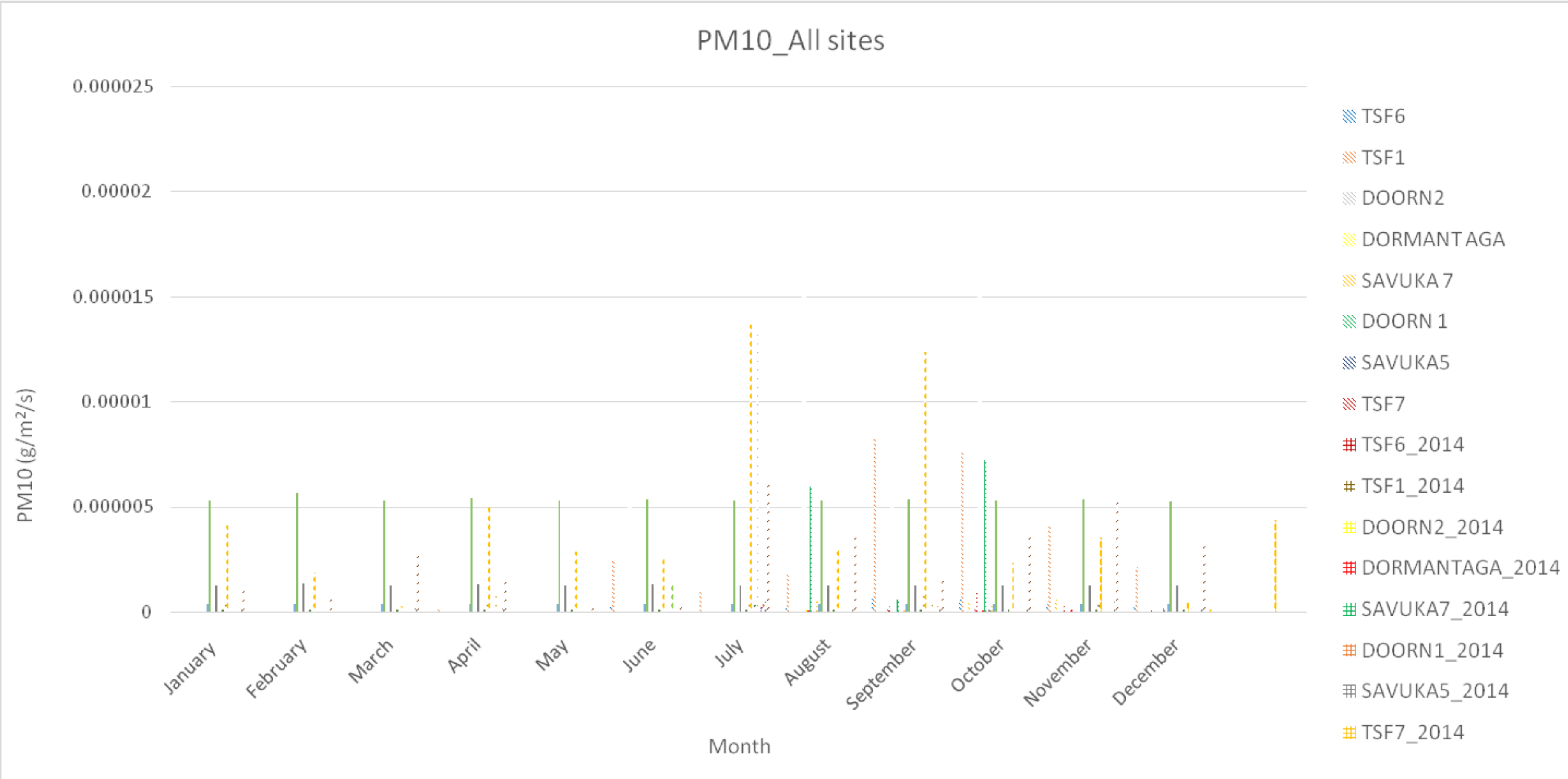
**Table 1:** XRF results for tailings storage facilities.

| Composition | $SO_3$% | $TiO_2$ % | $Al2O_3$% | CaO% | $Fe_2O_3$% | $K_2O$% | MgO% | MnO% | $Na_2O$ % | $P_2O_5$% | $SiO_2$% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Location** | | | | | | | | | | | |
| TSF7 | 0.27 | 0.30 | 5.70 | 0.41 | 2.86 | 0.65 | 0.76 | 0.06 | 0.15 | 0.06 | 85.32 |
| TSF6 | - | 0.26 | 4.61 | 0.24 | 2.23 | 0.59 | 0.58 | - | 0.08 | - | 90.37 |
| TSF1 | - | 0.32 | 5.22 | 0.21 | 2.25 | 0.64 | 0.55 | - | 0.09 | - | 89.00 |
| DORMANT AGA | - | 0.44 | 5.61 | 0.49 | 3.47 | 0.65 | 0.96 | - | 0.22 | 0.05 | 86.44 |
| SAVUKA 7 | 0.62 | 0.43 | 7.07 | 0.90 | 4.26 | 0.90 | 1.02 | 0.12 | 0.27 | 0.05 | 80.08 |
| SAVUKA 5 | 5.37 | 0.35 | 6.48 | 1.24 | 3.56 | 1.40 | 3.76 | - | 3.11 | 0.06 | 65.94 |
| DOORFONTEIN 1 | 0.14 | 0.38 | 7.88 | 0.55 | 3.78 | 1.05 | 1.47 | - | 0.16 | - | 81.60 |
| DOORNFONTEIN 2 | - | 0.24 | 3.60 | - | 1.20 | 0.38 | 0.12 | - | - | - | 93.29 |

**Table 5:** ICP-MS results for tailings storage facilities.

| Composition | K 39 ppb | Cr 52 ppb | Mn 55 ppb | Fe 57 ppb | Ni 60 ppb | Zn 66 ppb | As ppb | U 238 ppb | Se ppb | Cd 11 ppb | Au 197 ppb | Pb 208 ppb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Location** | | | | | | | | | | | | |
| TSF7 | 375.22 | 49.43 | 687.56 | 14737.49 | 194.58 | 182.23 | 32.15 | 50.50 | 1.47 | 0.53 | 0.49 | 7.55 |
| TSF6 | 241.43 | 51.18 | 126.28 | 14865.82 | 28.85 | 21.16 | 30.06 | 3.77 | 0.31 | 0.03 | 0.10 | 4.40 |
| TSF1 | 298.66 | 45.95 | 77.45 | 11906.95 | 23.70 | 37.57 | 18.24 | 12.25 | 0.24 | 0.03 | 0.26 | 4.60 |
| DORMANT AGA | 283.03 | 59.96 | 162.83 | 17229.47 | 45.07 | 30.68 | 24.09 | 22.00 | 0.69 | 0.07 | 0.27 | 10.86 |
| SAVUKA 7 | 923.90 | 129.19 | 1110.43 | 29434.75 | 75.34 | 71.53 | 30.01 | 67.28 | 0.55 | 0.13 | 0.35 | 27.35 |
| SAVUKA 5 | 3644.52 | 75.84 | 210.75 | 20048.29 | 70.84 | 54.12 | 29.86 | 76.074 | 0.48 | 0.18 | 0.46 | 21.86 |
| DOORFONTEIN 1 | 359.15 | 70.28 | 164.24 | 15235.13 | 51.66 | 43.42 | 18.37 | 4.05 | 0.37 | 0.07 | 0.06 | 5.54 |
| DOORNFONTEIN 2 | 197.51 | 14.62 | 14.54 | 3605.72 | 6.126 | 6.29 | 8.11 | 6.84 | 0.60 | 0.04 | 0.11 | 2.55 |





PM10_All sites
0.000025
0.00002
0.000015
0.00001
0.000005
0
PM10 (g/m2/s)
January
February
March
April
May
June
July
August
September
October
November
December
Month
TSF6
TSF1
DOORN2
DORMANT AGA
SAVUKA 7
DOORN 1
SAVUKA5
TSF7
TSF6_2014
TSF1_2014
DOORN2_2014
DORMANTAGA_2014
SAVUKA7_2014
DOORN1_2014
SAVUKA5_2014
TSF7_2014