Classification of PM_{10} and fall out dust sampling in the iron ore mining industry, Northern Cape province of South Africa

by

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Declaration

I, Johannes Jacobus Rautenbach, identity number , with student number hereby declare that this research project submitted to the Central University of Technology, Free state, for the Degree of Master of Science in Environmental Health, is my own and independent work. This work complies with the code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State. It has not been submitted before to any other institution by myself or any other person for attainment of a qualification.

Johannes Jacobus Rautenbach

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I certify that the above statement is correct.

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Abstract

Introduction: Fall-out dust is present in the iron ore mining industry and are generated by open cast mining activities and regulated by legislation. The aim of this study was to determine the concentrations of different dust types deposited at various dust monitoring points.

Methods: Single dust bucket (SDB), and multi directional dust bucket (MDB) methods were used to collect the dust samples. The collected dust was further evaluated for particulate matter smaller than 10 µm (PM_{10}) and analysed for the chemical composition of iron ore fall-out dust with possible impacts on humans and the environment. The influence of environmental parameters on the dust concentrations was also determined. Monitoring was conducted over a twelve-month period. The SDB method was sampled at eight different monitoring points and the MDB method at four monitoring points. Fall-out dust concentrations were determined for all dust sample collections. The sample concentration values were compared to the limit values of the South African National Standard 1929, ambient air quality limits for common pollutants. PM_{10} monitoring was done at three monitoring points. The chemical analyses of sampled dust for 42 elements was done at an accredited laboratory. The data on environmental parameters used in this study were collected from a centrally located weather station.

Results: The mean dust concentrations for SDB and MDB never exceeded the limit of 600 mg/m²/day for residential areas. The highest level for mean SBD was recorded in November when the wind speed was relatively high. The highest level of mean MDB and mean SDB + MDB fall-out dust where recorded in September. The mean values for SDB, MDB and SDB + MDB were higher from August towards the end of the year as the mean wind speed and relative humidity increased from August. The mean PM_{10} concentrations never exceeded the limit and the highest level was

recorded in February, when the mean wind speed was the lowest with the mean relative humidity the highest of the study period. The highest mean total fall-out dust concentrations of were recorded in September when the predominant wind direction was south south west (SSW). August had the second highest mean total fall-out dust concentration when the wind was predominant in the opposite direction of North. More than 50% of months the wind blows from a predominant multi direction and bi-directional of north west north (NWN) and north east (NE). The mean total PM_{10} concentration of all the PM_{10} monitoring points was calculated per month. The fluctuation in the mean total PM_{10} concentrations per month was limited when the wind directions were multi-directional and bi-directional respectively. Elements with concentrations below the detectable level (BDL) of less than 0.0001 mg/kg had been excluded and only 25 elements are reported on. The results showed that there are only three elements namely calcium, iron and copper that had noticeable higher concentrations than the other elements.

Discussion and conclusion: One of the prominent findings of this study was that the individual buckets of the multi-directional dust bucket did not produce significant differences, making the use of this type of bucket redundant. From the results it could be thus concluded that using single dust bucket systems could be used to monitor in a mining environment. Interestingly, the PM_{10} concentrations never exceeded the limit in the year of study. Furthermore, concentrations of the chemical elements were within environmental and occupation exposure limits. However, copper and iron demonstrated noticeably high concentrations, with copper and iron concentrations exceeding both the environmental and occupational exposure limits at all sampling points. From this study, it can be concluded that wind direction does not has a major influence on the type of method used for measuring fall out dust. Although the limit was never exceeded, the results indicated that the use of the multi-directional bucket system seems to be redundant. Wind speed has an influence on the rate of PM_{10} dust particle depending on the monitoring point location in relation to dust producing

operations. Applicable legislation is needed to monitor the elemental chemical content of dust when conducting environmental sampling.

Chapter 1

Introduction

1.1 Introduction

Iron is one of the most abundant rock-forming elements, constituting about 5% of the earth`s crust. It is the key ingredient of steel and about 98% of the world's iron ore production is used for steel production (Taylor *et al*. 1988). Most of South Africa's iron ore reserves are located in the Northern Cape, adjacent to the Kalahari manganese field, where it is mined from the earth's crust. The Khumani iron ore mine (KIOM), in the Northern Cape, is located approximately 20 km south of the town of Kathu. This mine is jointly owned and controlled by African Rainbow Minerals Limited and Assore Limited. The KIOM replaces the older Beeshoek iron ore mine at Postmasburg in the Northern Cape as the main iron ore producer for Assmang Limited. The KIOM produces approximately 16 million tons of export quality iron ore each year (Assmang 2017).

Various processes are involved when extracting iron ore deposits. Open cast mining begins by first clearing the surface area of the mine with heavy equipment. Thereafter, pits are dug using heavy equipment in search of iron ore. Iron ore is then removed and refined using heat and removing any other minerals and rocks that are included in the ore (Assmang 2017). The extraction of iron ore from the earth's crust involves drilling, crushing, loading and hauling, conveyor belt transport of ore and screening and loading (Organiscak and Reed 2004). During all these processes, vast amounts of dust are generated that workers are exposed to (Petavratzi *et al*. 2005). The uncontrolled airborne dust is not only a serious health hazard, but also affects the productivity because of poor visibility and increased maintenance costs. In addition, the dust travels over long distances, causing deterioration of ambient air quality in and around the mining site (Sinha and Banerjee 1997).

When considering health issues, the amount of suspended material in the air is of particular importance. During the mining process, fine particles easily become airborne, particularly particles (particulate matter) finer than 10 µm (PM_{10}) (Copeland and Kawatra 2005). Dust particles with an aerodynamic diameter smaller than 10 µm (PM_{10} standard) are a health hazard to humans. When inhaled, these particles penetrate the alveoli of the lungs and can lead to a variety of respiratory diseases (Department of Health and Human Services 2011). Respiratory diseases, such as silicosis and bronchitis, are well-known diseases amongst iron ore miners with the occurrence of chronic bronchitis to be particularly prevalent amongst iron ore miners (Ädelroth *et al.* 2006, Hedlund *et al.* 2004). Silicosis is an interstitial fibrotic lung disease that is caused by a pulmonary response to the inhalation of respirable crystalline silica dust (Liu *et al.* 2013). Although there is a clear relationship between the cumulative exposure to silica and the risk of silicosis (Finkelstein 2000), the appearance and severity of silicosis may vary greatly amongst individuals (Yucesoy *et al.* 2001). Silica, a trace element of airborne dust, is an important parameter for the indication of health effects of dust.

At the KIOM mine near Kathu in the Northern Cape, little is known about the composition of dust and the worker dust exposure levels at various stages of the iron ore mining process. Because it is known that dust may be hazardous to human health, it is vital to obtain an understanding of the dust levels and dust composition at this mine.

1.2 Aim and objective

The major aim of this study was to determine the concentrations of different dust types deposited at various dust monitoring points on the premises of the KIOM. A secondary aim was to determine the chemical composition of fall-out dust and to ascertain the influence of environmental parameters on dust deposition.

To meet these aims, the following objectives were devised:

- To determine fall-out dust concentrations at different representative monitoring points on the premises of the KIOM;
- To determine the PM_{10} dust concentrations at different representative monitoring points on the premises of the KIOM;
- To determine the chemical composition of the collected fall-out dust at the representative monitoring points on the premises of the KIOM; and
- To determine the influence of environmental parameters on the concentrations of the different types of dust.

1.3 Structure of the dissertation

This dissertation comprises of six chapters. The layout of the dissertation is as follows:

Chapter 1: *Introduction*

In this chapter the research project is introduced, the problem stated, aim and the objectives presented.

Chapter 2: *Literature Review*

In this chapter a comprehensive review of the literature pertaining to the characterising of iron ore dust is provided.

Chapter 3: *Materials and Methods*

In this chapter all materials and methods used in this research project is presented.

Chapter 4: *Fall-out and Dust*

In this chapter the results of the sample concentrations of fall-out and PM_{10} dust, for a 12-month period are presented. These results are also compared to the South

African National Standard 1929 of 2011 and discussed. The chemical composition of the fall out dust is also presented.

Chapter 5: *Influence of Environmental Factors on Dust Deposition*

In this chapter the influence of meteorological parameters on the concentrations of different dust types was presented and discussed.

Chapter 6: *Recommendations and Conclusions*

In this chapter recommendations are made and concluding remarks are presented on fall out and PM10 dust deposition, chemical composition together with influences of metrological parameters on dust deposition.

Appendix A: In this appendix, a description of the microbalance operating procedure that was used for calculating fall-out dust and PM_{10} concentrations is presented.

Appendix B: In this appendix, the operating procedure and method to obtain fall-out dust measurements is presented.

Chapter 2

Literature Review

2.1 Introduction

Iron is the fourth-most abundant element, comprising approximately 5% by mass of the earth's crust. Iron ore production makes a significant contribution to the global and local economy (Taylor *et al*. 1988). Since 2012, iron mining has become the world's second most traded commodity after oil, with a market size of over three trillion dollars in 2012 alone. South Africa is the seventh largest producer of iron ore and has traditionally been the fourth largest exporter worldwide (Booyens 2013).

The use of iron ore dates back 5 000 years when its use in an iron blade was discovered in an Egyptian pyramid. This discovery indicates that Egyptians were probably skilled steel workers who built the great pyramids and other monumental architectural structures. The industrial use of iron ore can be dated back to 800 BC, marking the start of the Iron Age (Taylor *et al*. 1988).

Iron ore has been mined and smelted in South Africa since pre-historic times. Evidence of mining in South Africa can be found in remains of ancient workings, primitive furnaces, and accumulations of slag at locations scattered across South Africa, with a concentration in the previously known northern Transvaal (Taylor *et al.*, 1988). Significant geological exploration began in South Africa soon after the discovery of diamonds in 1867. Five years later, the surveyor George W. Stowe, a geologist and ethnologist, discovered useful iron ore and coal deposits in the then Orange Free State (Adams and Morral, 2010). The first iron ore steel plant was opened in 1918 after Cornelius Delfos obtained the rights to mine low-grade iron ore near Pretoria (Wells Digby Assosiates 2008). In 1928, the Iron and Steel Corporation of South Africa (ISCOR) was established and governed under an Act of Parliament. After the depletion of this Iscor mine, two other mines were established in 1932

and 1954. With the growth of the iron ore industry, other companies were also established, such as the Highveld Steel and Vanadium Company in 1957, and Associated Manganese (Assmang) in 1964 (Bodley *et al*. 2013).

2.2 Present-day iron ore mining in South Africa

South Africa has extensive iron ore deposits. The principal deposits of iron ore can be found in the Superior type banded formations of the Transvaal Super group in the Northern Cape Province. These formations can be traced as a prominent range of hills, visible for some 400 km from Pomfret in the Northwest Province to Prieska in the Northern Cape Province. The most significant deposits occur in Northern Cape Province in the vicinity of Postmasburg and Kathu (Bonga 2005). These iron ore reserves are adjacent to the extensive manganese fields of the Kalahari. Most of the iron ore mined from this deposit is earmarked for export and is transported via a purpose-built rail link to Saldanha Bay on the Atlantic Ocean, more 800 km from the mine (Chamber of mines 2017).

The earth's core contains mostly metallic iron, but in the crust iron reacts with other substances and the free metal is rarely found, thus iron can be found as a constituent of many mineral species, in water, plants and blood (Taylor *et al*. 1988). The widespread distribution of iron is a result of the fact that it easily combines chemically with many other elements in a range of physical and chemical environments. Although common ore- and rock-forming minerals contain appreciable amounts of iron, only seven of these contain sufficient amounts that can be mined economically. These ore- and rock-forming minerals include hermatite, magnetite, goethite, siderite, limonite, lepidocrocite and chamosite. The most important of these are hermatite, magnetite and goethite (Chamber of mines 2017).

Most iron ore mining operations in South Africa are open cast, also known as open-pit. The mining lifecycle comprises of a number of phases. These phases include, geological exploration,

development of the mine, mining operation, disposal of overburden and waste rock, ore extraction, beneficiation, tailings and disposal, site reclamation and closure. The exploration phase includes surveys, field studies, and drilling test bore holes, as well as exploratory excavations. In the development phase access roads are constructed, the mining site is prepared and cleared. Active mining comprises of two phases: the extraction and concentration (or beneficiation) of the metal from the earth. During the first phase of the mining operations the overburden is excavated to allow access to the ore deposit. This excavation process generates high volumes of waste, usually deposited on-site, either in piles or on the surface or as backfill in open pits. Ore extraction is accomplished by using specialised heavy equipment and machinery, such as loaders, haulers, and dump trucks, which transport the ore to processing facilities using haul roads. The next phase in mining involves the grinding or milling of the ore, thereby separating the relatively small quantities of iron from the non-metallic material of the ore in a process referred to as beneficiation. Beneficiation is one of the most costly parts of a mining operation, and results in very fine particles that allow better extraction of the iron. The beneficiation process produces high-volume waste called tailings. When active mining ceases, mine facilities and the site are reclaimed and closed (Chamber of mines 2017).

2.3 Mine dust

Dust is a generic term that is used to describe fine particles that are suspended in the atmosphere. Dust is formed when fine particles become airborne by the action of wind, disturbance of fine materials, or through the release of particulate-rich gaseous emissions (Wentzel 2015). Dust particles are small solid particles that are projected into the air by natural forces, such as wind, volcanic eruption, and by mechanical or man-made processes such as crushing, grinding, milling, drilling, demolition, shovelling, conveying, screening, bagging, and sweeping. To be projected into the air, dust particles are usually in the size range from about 1 to 100 µm in diameter, and they

settle slowly under the influence of gravity (Calvert 1990). In contrast, the WHO (1999) takes into consideration the aerodynamic diameter of dust particles and therefore regards the maximum size for dust particles as 75 µm in diameter.

Open cast mines generate vast volumes of mine dust, which is generated when fine soil or rock particles are disturbed during mining activities (Petavratzi *et al.* 2005). The amount of dust generated is influenced by the type of mining activities performed, environmental factors, as well as the geographical position of the mine. Mining activities that are mainly responsible for dust generation include, bush clearing, topsoil and overburden removal, drilling, blasting, crushing, as well as loading and hauling of materials onto road transport vehicles (Petavratzi *et al.* 2005).

2.4 Classification of dust

Different fields of study classify dust differently. Classifications of dust in the environmental- and occupational hygiene field include total suspended particulate matter (TSP), nuisance dust and fugitive dust. Total suspended particulate matter refers to all airborne dust particles that by means of breakdown processes are suspended in the air. The particle size of TSP matter usually has an aerodynamic diameter (AD) of 40-50 µm (Petavratzi *et al.* 2005 and Slanina 2006). Nuisance dust is a term used historically by the ACGIH (American Conference of Governmental Industrial Hygienists), to describe any airborne coarse particles, which have little harmful effect on the lungs and do not produce significant disease or harmful effects when exposures are kept under reasonable control. However, that may lower environmental quality, damage machinery or functions as a physiological irritable substance in the atmosphere. Fugitive dust describes dust particles often generated from unconfirmed sources that escape capture and is often found outside the boundaries far from the generation sources. Dust generated from mines is typically fugitive dust (Wentzel 2015). Different mining activities generate different amounts of dust. In open cast mining, besides the dust generation mining activities such as drilling, crushing, loading and unloading of material; the removal

of topsoil and overburden, and the transport of this material, may all contribute to dust emissions. These atmospheric particles consist of a variety of complex mixtures of particles and gasses where the primary particles are discharged directly from their source, while secondary particles are formed in the atmosphere (Davidson *et al*. 2005).

Another classification of dust is typically by particle size, rather than by composition. There are several size categories of dust. These categories include (Badenhorst 2013; Wentzel 2015):

- Deposited matter refers to any dust that falls out of suspension in the atmosphere.
- Total suspended particles (TSP) typically refer to particles 50 µm (0.05 mm diameter) in size or less.
- Particulate matter 10 µm (0.01 mm) in size or less are referred to as PM_{10}.
- Particulate matter 2.5 µm (0.0025 mm) in size or less are referred to $PM_{2.5.}$
- Nanostructured particles are particles with a physiochemical structure larger than that of the atomic- or molecular dimensions, but smaller than 100 nm, which still adhere to their physical- , chemical- and biological properties.

2.4.1 Chemical composition of atmospheric dust

Iron ores are represented as rocks and minerals from which iron can be extracted through mining processes for commercial use. The iron found in iron ore mainly occurs in iron-oxide compound forms (Liu *et al*. 2013). The iron ore mainly comprises the iron oxide minerals such as hematite, Fe_2O_3 (70% Fe); goethite, Fe_2O_3sH2O, (63% Fe); limonite, a mixture of hydrated iron oxides (up to 60% Fe); and magnetite, Fe_3O_4 (72% Fe) (Liu *et al*. 2013). Hematite is red in colour and occurs in all forms, from solid rock to loose earth. Magnetite is black in colour, goethite is brown in colour and limonite is a yellow-brown ore which is a mixture of impure goethite and hydrated iron oxides (Badenhorst 2013). Hematite originates in a variety of rock forms but is most abundant in

sedimentary banded-iron formations. The iron extracted from hematite ore is used for the production of steels and alloys like ferroalloys, ferrosilicon and ferromanganese (Cairncross 2004).

Airborne dust that arises from iron ore mining consists mostly of iron ore together with clays (aluminosilicate and iron silicate) and quartz. The only comprehensive chemical analysis of airborne emitted from an iron ore mine was sourced after an extensive literature search. A sample of representative dust was taken from the combined iron ore mines near Port Hedland, Western Australia (Goverment of the Western Ausrlian Department of Health 2016). This analysis showed that most of the airborne dust comprised of iron oxides (haematite and goethite) as well as clays (aluminosilicates and iron silicates) and quartz (as chert). The quartz (as chert) is in the >2 µm size range. The chemical (elemental) composition of iron ore is Fe, which occurs as a mixture of oxides (magnetite, haematite and goethite). Other chemicals include the oxides, SiO2, Al2O3, TiO2, CaO, MgO, MnO. The Si and Al are likely to be present as clay minerals. The quartz is most likely chert. The chemical compounds that are the principle contributors of iron-ore dust toxicology are iron oxide and silica (Banerjee *et al.* 2016).

2.4.2 Airborne particulate matter in relation to occupational hygiene

Although the term "airborne dust" is used, in the related field of environmental hygiene, concerned with pollution of the general atmospheric environment, the term "suspended particulate matter" is often preferred (WHO 1999 and 2000). In the field of occupational hygiene, airborne particulate matter is sampled to determine the concentration of particulate matter that a worker may inhale during exposure. In the past particulate matter sampling comprised of determining only total mass sampling, however, in the (WHO 2000) early 1990‘s the criteria for size-selective sampling became internationally accepted for sampling. This sampling strategy takes specific regions of the respiratory tract into account (European Committee for Standardization 1993; International Organization for

Standardization 1995). This strategy led to a better understanding of respiratory deposition and resulting health effects of different particle sizes (Badenhorst 2013).

When airborne particles are inhaled into the respiratory tract, their size determines where they are deposited along the respiratory tract. In terms of occupational hygiene, deposition of particles is expressed in three different size fractions: inhalable, thoracic and respirable particulate mass (PM), (Petavratzi *et al*. 2005; Belle and Stanton 2007; Mark 2008). Inhalable PM refers to the amount of particles in a cloud of dust that can be inhaled through the nose and mouth with an aerodynamic diameter of up to 100 µm. Examples of dusts for which any inhalable particle is of concern include certain hardwood dusts (which may cause nasal cancer), and dusts from grinding lead containing alloys (which can be absorbed and cause systemic poisoning) (WHO 1999). Thoracic PM refers to the particles with an aerodynamic diameter of <30 µm. These particles can penetrate the airways of the head and the lungs and could result in adverse health effects when deposited in the lungs in the alveoli. Examples of dusts for which this fraction is of particular concern include cotton and other dusts causing airway disease (WHO 1999). Respirable PM refers to the particles with an aerodynamic diameter up to 10 µm. These particles can penetrate beyond the terminal bronchioles into the gas-exchange region of the lungs. Examples of dusts for which the respirable fraction offers greatest hazard include quartz and other dusts containing free crystalline silica; cobalt-containing and other hard metal dust produced by grinding masonry drill bits; and many others (WHO 1999).

In the occupational hygiene context, sampling of airborne particles focusses mainly on the inhalable, thoracic and respirable particles. Because of technical advances in recent time new scientific development has identified a fourth sampling category, namely the sampling of ultrafine particles (UFP). UFP are nanoparticles with sizes smaller than 100 nm. These particles may transverse the alveolar boundary and enter the pulmonary systemic blood circulation (Buzea *et al*. 2007).

In occupational hygiene, particle size is especially important. Particle size gives an indication of particle deposition in the body and biological effect (Oberdörster *et al*. 1994; Maynard and Kuempel 2005). The shape of the particle is determined from its source of origin or formation process. The majority of particle shapes are irregular and complex (Morawska and Salthammer 2003). Therefore, using particle diameter alone to describe particle size is an over simplification, since the geometric size of a particle does not fully explain how airborne particles behave. The most appropriate measure of particle size, is particle aerodynamic diameter. The aerodynamic diameter is defined as "*the diameter of a hypothetical sphere of density 1 g/cm^3 having the same terminal settling velocity in calm air as the particle in question, regardless of its geometric size, shape and true density*" (WHO 1999). The aerodynamic diameter expressed in this way is appropriate because it relates closely to the ability of the particle to penetrate and deposit at different sites of the respiratory tract (WHO 1999).

2.4.3 Transport and dispersion of dust

Opencast mining creates wider air quality deterioration due to dust and gaseous pollutants in and around the mining complexes (Singh and Pal 2010). Unit operations such as drilling, blasting, loading, transport, and unloading, produce particulate matter (PM) in diverse size ranges that are harmful for human health and surrounding environment (Gautam *et al*. 2015). Primary PM is emitted directly into the surrounding air, while secondary PM can also be formed in the atmosphere from gaseous precursors such as sulphur dioxide, oxides of nitrogen, ammonia and non-methane volatile organic compounds (WHO 2013). Although primary PM and the precursor gases can be from natural source (non-anthropogenic), opencast mining contributes large volumes of primary PM to the air (anthropogenic source).

Csavina (2012) argues that contamination of the air by PM is of global concern. Air masses containing large amounts of dust frequently cross continental and international boundaries and often

have adverse environmental consequences in downwind depositional areas (Csavina *et al.* 2012). The potential for air to transport contaminants long distances is far greater than surface water, groundwater, and most biological vectors, because contaminants can be transported rapidly and within hours and days (Csavina *et al.* 2012). Atmospheric dust plays a major role in transporting contaminants over longer time periods (years to decades) and at smaller spatial scales (meters to kilometres). Probably the most notable transporter of contaminants is the air, because of the potential speed, distance, and aerial extent (Csavina *et al.* 2012).

Particulate matter transported by air is found in a wide range of sizes (Kumar *et al.* 2010 and 2011). Particles larger than 500 µm in diameter fall down rather quickly due to gravitational settling (Patra *et al.* 2016), while particles that are smaller than <0.5 µm in diameter are small enough to remain in suspension and adhere onto the surface of other particles (Kumar *et al.* 2012). Particulate matter between 0.1 and 1 µm in diameter can remain in the atmosphere for days or weeks and are thus be subjected to long-range transport by air (WHO 2013). Particles in between in size are distributed differently depending on the source minerals (Patra *et al.* 2016). Particles of 30 µm and larger are very coarse particles that settle very close to the point of emission. Particles with sizes between 30 and 10 µm remain suspended for a limited time in air. However, particles smaller than 10 µm (PM_{10}) are more likely to be inhaled through the respiratory tract. Particles smaller than 2.5 µm ($PM_{2.5}$) and fine particles up to 1 µm (PM_1) can be inhaled deep into the lungs (Dockery *et al.* 1993; Dockery and Pope 1994). Thus, PM_{10}, that includes $PM_{2.5}$ and PM_1, is responsible for the reduced air quality that results in adverse effects on human health (Tiwari *et al.* 2012). Few studies exist that have quantified the different sizes of PM in the air near opencast iron mines. Patra *et al.* (2016) studied PM_{10} and smaller PM emitted from two large iron ore mines in eastern India and found that while the background PM level was dominated by the fine fractions, PM_1 and $PM_{1–2.5}$ of the respirable particle, the emissions from the mining consisted mainly of the coarse fractions $PM_{2.5–10}$ of the respirable particle.

Environmental factors contribute greatly to the amount of dust that is generated at dust sources. Wind, in particular, contributes to dust generation by mobilising dust particles from stockpiles, tailings and exposed areas (Holden 2006). Fine dust from blasting mine operations may be carried by ventilating air over great distances, which is not the case for larger and heavier particles. These fine PM may settle permanently on land or only temporarily, before being picked up by wind and moved again, from where they can settle on land again or in water, where they may dissolve. Particulate matter also tend to either stick together or break apart during distribution or redistribution and thus change size. Besides, the possibilities of changing size, PM may undergo chemical changes and reactions with other substances, depending on their composition (Wentzel 2015). PM smaller than 1 µm have a settling velocity of 0.003 µm/sec. Movement of these particles in airstreams is more important than gravity sedimentation (WHO, 1999). Particles larger than 50 µm have a terminal velocity of >7cm/sec. These particles do not remain airborne very long, depending on the conditions. Particles larger than 100 µm can also become airborne; however, they remain airborne only for a short period (Badenhorst 2013).

There is a growing body of research indicating the importance of relative humidity on dust emissions and, consequently, atmospheric dust levels. At relative high wind speeds, a definite trend has been observed between dust concentration and relative humidity; dust concentration increases with relative humidity, reaching a maximum around 25% and subsequently decreases with relative humidity (Csavina *et al.* 2014; Giri *et al.* 2008). The atmospheric pressure, wind velocity and humidity were found to be significant factors compared to others influencing PM_{10}. Increase of rainfall and humidity has negative correlation with average PM_{10} concentration in Kathmandu valley. The study also infers that the wind speed and atmospheric pressure inducing increment of average PM_{10} concentration in Kathmandu Valley (Giri *et al.* 2008).

Airborne dust can be transported through the atmosphere by different mechanisms. Airborne dust can be transported from the dust source by means of surface creep, saltation and suspension (Csavina *et al*. 2012). The type of transport mechanism is dependent on particle size (Field *et al*. 2010). Larger particles of sizes >2 000 µm are usually transported by surface creep, while particles of sizes from 60 µm to 2 000 µm are transported by means of saltation (Stout and Zobeck 1996). The larger particles are influenced to a lesser extent by air movement and settle on the earth's surface in considerable numbers (Calvert 1990). Finer particles tend to collide with one another, forming larger particles, which may settle on the earth's surface. Particles <60 µm are transported by means of suspension and may be transported over long distances (Chadwick *et al*. 1999). Some particles, particularly the smaller sizes, <10 µm, may remain airborne for considerable periods because of thermal air movement and turbulence (Sibanda 2003).

There are two different processes that lead to the removal of dust from the atmosphere. Dry deposition occurs when particles settle by gravitational forces and turbulent mixing. Mostly, particles of sizes >10 µm settle through dry deposition. These particles do not remain airborne for a long time and tend to settle close the dust generating source. Wet deposition, on the other hand, occurs when dust settles because of rain (Portmann *et al*. 2009). Particle of sizes ≤10 µm usually settle within one kilometre from a dust generating source when mechanically disturbed, although thermals and high wind speeds may blow dust of these sizes to further distances. In particular, dust generated from a stack can travel great distances. The distances that such dust travels depend on the height of the stack from ground level, the size of the particles, and the topography of the area (Kuhn and Loans 2013).

2.5 Deposition of airborne particulates in the respiratory tract

2.5.1 Respiratory regions and particle deposition

Airborne dust particles enter the human respiratory pathway by inhalation of the particles through the nose and mouth. Dust particle penetration, deposition, retention time and rate of clearance in the respiratory tract, as well as the rate of absorption into the pulmonary circulatory system and accompanying tissues depends on the physical and chemical properties of inhaled airborne particulates, such as shape and surface properties (Pang *et al.* 2003). Several physiological factors also play a role in the penetration, deposition, retention time, rate of clearance and pulmonary circulatory absorption of inhaled dust particles. These factors include breathing pattern at the time of inhalation and the state of health of the tissues in the respiratory tract. A respiratory tract may have deteriorated as a result of disease or unhealthy habits such as smoking (Badenhorst 2013).

When studying the deposition of dust particles throughout the respiratory tract, various particle deposition models have been constructed. These models describe dust deposition in terms of three regions in the respiratory tract; The head airways region (HAR), also called the extra-thoracic (ET) or nasopharyngeal region, is the primary area for particle inhalation, consisting of the nose and mouth and serves as the entrance of the trachea (Lazaridis and Colbeck 2010 and Colbeck 2010). When a person is breathing normally, air is inhaled through the nose and pharynx into the larynx. However, in instances of nasal obstructions, additional air will be inhaled through the mouth, which may lead to particle impaction of the mouth and throat area. The main task of the ET region is to clean the inhaled air before it moves further down the respiratory tract.

There are five mechanisms of particle deposition. These mechanisms are impaction, gravitational sedimentation, Brownian diffusion, interception and electrostatic diffusion (WHO 1999). When dust particles are inhaled, the larger particles are deposited in the nasal region by impaction on the hairs of the nose or at the bends of the nasal passages, or through sedimentation. Particles are removed

by impacting with the wall of the bronchi when they are unable to follow the gaseous streamline flow through subsequent branches of the bronchial tree (Terblanche 2009). For particles that are smaller than 0.5 µm, sedimentation and impaction are no longer relevant and the deposition occurs through Brownian diffusion. These particles pass through the nasal region and are deposited in the tracheobronchial and pulmonary regions. As the airflow decreases near the terminal bronchi, the smallest particles are removed by Brownian motion, which pushes them to the alveolar membrane Interception is mainly important only for fibres as they tend to align with the airstream lines (Badenhorst 2013). Figure 2.1 demonstrates the different mechanisms of dust deposition.

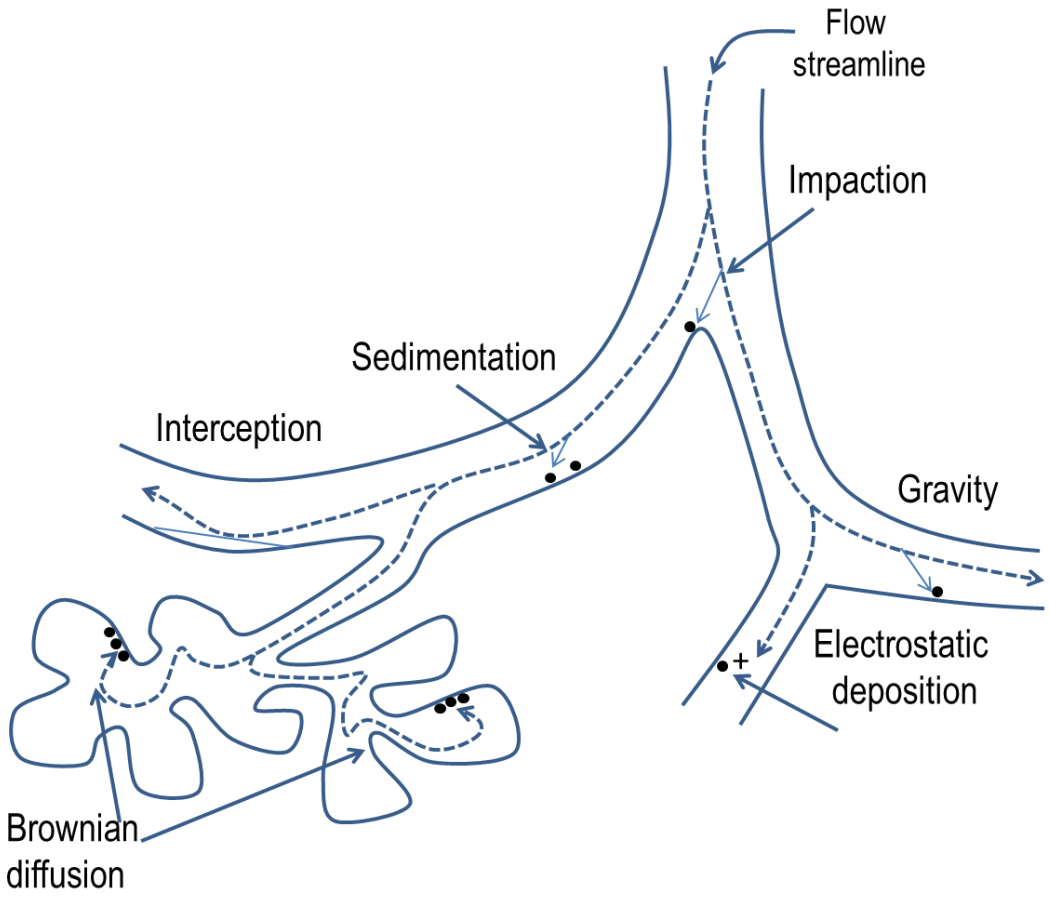


Figure 2.1 **Primary deposition mechanisms influencing inhaled particles in the respiratory tract (Adapted from Badenhorst 2013).**

2.5.2 Respiratory particle clearance mechanisms

Several dust particle clearance mechanisms function in the respiratory tract. In the upper airways of the pulmonary system particle clearance carried out through physical translocation of the non-soluble particles or by chemical clearance of soluble particles. Soluble particles interact with the lung wall lining mucus and dissolve and are then transported out of the respiratory tract. These dissolved particles can also be absorbed by the epithelial cells where they are then transported into the lymphatic or circulatory system (Lippmann *et al.* 2003). The clearance of non-soluble particles from the respiratory tract is much slower than the soluble particles. These particles become moistened when they encounter the respiratory tract lining. The moistened particles are then moved towards the epithelium by liquid-air interface forces that occur at the surface. The cilia of the epithelium cells in the nose move the mucus coated particles down to the throat and from the bronchi and trachea up to the throat. This process can take up to several hours and is known as the mucociliary escalator. At the throat the material first passes over the tonsils and is then swallowed and enter the gastro-intestinal tract, where most particles are destroyed by the gastro-intestinal acids (WHO 1999).

Inhaled airborne particles that are smaller than 10 µm can be deposited at the alveoli of the lower pulmonary system. These particles are cleared through macrophage phagocytosis. The rate of particle clearance is dependent on particulate size. Particles in the size range between 1.5 µm and 3 µm are considered to be optimal for macrophage clearance efficiency, while smaller particles are not cleared as efficiently. Macrophages in the lung alveoli transport particles to the mucociliary escalator or through the epithelium to the lymph nodes in the lungs or associated areas, where the particles can then be removed from the physiological system. Particles that reach the circulatory- and lymphatic systems can be distributed to organs, such as the kidneys, where clearance may occur through the organ-specific mechanisms (Schoeman and Van den Heever, 2014). In situations where chronic exposure to inhaled particles lead to the capacity of the clearance mechanisms of the pulmonary systems being overwhelmed, the excess particles induce lung burden which can initiate a

range of toxicological responses that will result in damage of the lung tissue (Lippmann and Chen 1998). The degree of these adverse health effects depends on the rate of particle

2.6 Health risk criteria

Particulate matter (PM) is the collective name for fine solid or liquid particles added to the atmosphere by processes at the earth's surface. Various international health risk criteria used for the assessment of inhalable particulate matter (PM_{10}). Guidelines and standards are provided for a 24-hour exposure and annual average exposure period respectively (Terblanche 2009).

Table 2.1 International health risk criteria used for the assessment of inhalable particulate matter (PM_{10}) (Adapted from Terblanche 2009).

Origin	24-hour exposure (µg/m³)	Annual average exposure (µg/m³)	Number of exceedance days/months allowed per year
Botswana		100	Monthly average 200 µg/m³
RSA	180[1]	60[1]	3 daily exceedances
SANS	75[2] 50[2,3]	40[2] 30[2,3]	Still to be determined
World Bank[6]	500	100	NA
EU[7]	50	30 20[5]	25 daily exceedances By 2010 only 7 daily exceedances
US-EPA[8]	150	50[9]	1 daily exceedance
UK[10]	50	40	35 daily exceedances
WHO[11,12,13]	50	20	NA

(1) Standard laid out in the National Environment Management: Air Quality Act. No. 39 of 2004:
(2) As outlined by the South African National Standards (SANS). 1929:2005 - Ambient air quality – limits for common pollutants.
(3) Target Level
(4) As prescribed under the old guidance documentation, prior to these limits being adopted by the Act.
(5) Compliance by 1 January 2010
(6) World Bank Air Quality Standards summary obtainable at URL: http://www.worldbank.org/html/fpd/em/power/standards/airqstd.stm#paq.
(7) European Union Air Quality Standards summary obtainable at URL:

http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexplus!prod!DocNumberandlg=enandtype_doc=Directiveandan_doc=1999andnu_doc=30.

(8) United States Environmental Protection Agencies National Air Quality Standards obtainable at URL: http://www.epa.gov/air/criteria.html

(9) To attain this standard, the 3-year average of the weighted annual mean PM10 concentration at each monitor within an area must not exceed 50 ug/m^3.

(10) United Kingdom Air Quality Standards and objectives obtainable at URL; http://www.airquality.co.uk/archive/standards.php

(11) WHO = World Health Organisation

(12) Guidance on the concentrations at which increasing, and specified mortality responses due to PM are expected based on current scientific insights (WHO, 2005).

(13) Air quality guideline

2.7 Health effects of dust

The impact of particulates on human health is largely dependent on, particle aerodynamic properties and chemical composition. Aerodynamic properties of particles are influenced by the size, shape and density of the particles. Whether particles will be inhaled is a function of the aerodynamic characteristics of particles in air flow streams, while the place where particles will be deposited in the respiratory tract is on their size (Terblanche 2009). Dust particles that enter the respiratory tract are not completely harm less. Wherever the particles are deposited, either in the head or in the lung, they have the potential to cause harm either locally or subsequently elsewhere in the body (WHO 1999). Even low particle concentrations can result in adverse effects. Whether particles result on adverse effects are depended on you long they remain in the respiratory tract. Smaller particles result in higher toxicity than larger particles of the same elemental composition and structure, with the toxicity increasing with decreasing particles size (Badenhorst 2013). Smaller particles are thus more reactive and will generate oxidative stress between the particles and the fluid of the lung wall lining, as well as particle contact with cells, thus leading to an increase of inflammatory reactions in the lungs (Gilmour *et al.* 1996; Kreyling *et al.* 2006).

Adverse reactions include inflammation, impaired macrophage clearance and epithelial cell proliferation that will lead to pathologies such as fibrosis, emphysema and tumour development. The extent of the adverse health effects on the physiological system may be dependent on genetic susceptibility and health status of an individual (Badenhorst 2013). Numerous epidemiological

studies indicated that dust exposure at iron ore mines is associated with cardiorespiratory diseases (Chau *et al.* 1993; Hedlund *et al.* 2004; Su *et al.* 2006; Bjor *et al.* 2009; Liu 2013). A study carried out among workers at an open-cast iron mine in South Goa revealed that 0.6% workers had pneumoconiosis, 3.2% had abnormal spirometry findings, 38.16% had hearing loss and 27.7% had defective vision respectively (Oliveira *et al.* 2014). Dust particles have also been shown to have a significant association with increased hospitalisation, mostly relating to respiratory conditions. Associations with cardiovascular disease were also shown, but the magnitude was generally lower than for respiratory disease (Gilmour *et al.* 1996; Kreyling *et al.* 2006).

Siderosis is an important occupational disease. It is a lung disease that is a form of pneumoconiosis. This disease results from the inhalation of iron particles. The inhaled particles settle in the lungs, lead to lung inflammation and scarring, and eventually cause the lungs to stiffen and become hardened, resulting in breathing difficulties (WHO 1999). Moreover, it has been established that toxic heavy metals may also affect the central nervous, renal, and reproductive systems (Papanikolaou *et al.* 2005).

2.8 Environmental effects

Atmospheric dust, usually in the particle size range <60 μm, can play an important role in the transport of environmental contaminants. Large dust events have the potential to transport large amounts of contaminants rapidly over long distances (Csavina *et al.* 2012). These contaminants represent a unique risk to the environment and human health. Besides affecting humans and animals, soil, water and plants are also affected. Heavy metal contamination from mining activities are a major problem in many countries (Dudka and Adriano 1997; Djebbi *et al.* 2017). Heavy metal laden dust may adversely affect agricultural soils. These pollutants will undergo a series of physical, chemical and biological reactions with soil active components, including adsorption, complexation, precipitation and substitution. Thus, the mobility and toxicity of heavy metals in soils depend not only

on their total concentration, but also strongly on their specific chemical forms, metal types, environmental factors and soil properties like pH, organic matter content and type and redox conditions (Nyamangara 1998; Gleyzes *et al*. 2002; Yin *et al*. 2016).

Atmospheric dust effects vegetation in various ways. The primary effects are reduced growth and productivity, because of interference with photosynthesis and phytotoxic impacts as a result of particle composition (Terblanche 2009). The mechanisms are through smothering of the leaves, physical blocking of the stomata, bio-chemical interactions; and ıindirect effects through the soil. Coating with dust may cause abrasion and radiative heating and may reduce the photosynthesis. Acidic and alkaline materials may cause leaf surface injury, while other materials may be taken up across the cuticle. Metabolic uptake from the soil could impact vegetation and ecosystems adversely by mainly influencing nutrient cycling, especially that of nitrogen. In the agriculture sector, high concentrations of dust can cause injury to plants, reduced growth and yield, and may lead to premature death of plants (Terblanche 2009). Mineral dust is also believed to have impacts on the nutrient dynamics and marine biogeochemical cycling processes (Falkowski *et al*. 1998; Bishop *et al*. 2002).

2.9 Air quality legislation

2.9.1 International standards and guidelines for ambient air quality

Legislation is fundamental in the regulation of effective air quality management and is the link between the atmospheric emission source and the receptor downstream. Air quality guidelines indicate the safe daily exposure levels for a population, from the very young to the elderly, and for the lifetime of an individual (WHO 2000).

Legislation is necessary to control dust deposition. Guidelines and standards for air quality management provide the link between the source of atmospheric emissions, and the user of that air downstream. These guidelines indicate the safe daily exposure levels for a population of all age groups and are normally given for a specific averaging period (WHO 2000). This average period is the time span over which the air concentration was monitored at a specific location. There are five averaging periods applicable namely instantaneous peaks, one-hour average, 24-hour average, one month or 30-day average, and annually average. Guidelines are normally given for maximum daily and annual averaging periods for particulates. The European standards (Table 2.1) has been determined through consultations, taking into account environmental conditions, and economic and social development of different regions, the importance of a phased approach to attaining compliance. These air quality standards are based on clinical, toxicological and epidemiological evidence (US-EPA 2000).

Table 2.2 Nuisance dust mass deposition measurements (US EPA 2002).

Authority	Pollutant	Concentration limits	Relevance
UK dust deposit rate	All particulates	200 mg/m²/day	Serious nuisance
West Australian nuisance standard	Al particulates	133 mg/m²/day	First loss of amenity
		333 mg/m²/day	Unacceptable reduction in air quality

West Germany nuisance standard	All particulates	350 mg/m²/day	Possible nuisance
		650 mg/m²/day	Very likely nuisance
Malaysia air quality standard	All particulates	133 mg/m²/day	Nuisance dust deposit

2.9.2 South African standards and guidelines for ambient air quality

The South African National Standards (SANS) 1929:2011, Edition 2 (SANS 1929:2011) indicates the dust deposition criteria. This standard also stipulates that dust fall rates will be evaluated against a four-band scale for fall-out dust, (Table 2.2) that indicates target, action and alert concentrations.

Table 2.3 Four-band scale evaluation criteria for dust deposition (SANS 1929:2011).

Band Number	Band description label	Dust fall rate (D) (mg/m²/day)	Comment
1	Residential	D<600	Permissible for residential and light commercial
2	Industrial	600<D<1 200	Permissible for heavy commercial and industrial
3	Action	1 200<D<2 400	Requires investigation and remediation if 2 sequential months lie in this band, or more than 3 occur in a year

4	Alert	2 400<D	Immediate action and remediation required following the 1st incidence of dust fall rate being exceeded. Incident report to be submitted to relevant authority

There are thresholds (Table 2.3) also set for the different exposure areas in this legislation that needs to be complied to. The guidelines state that it is permissible for heavy commercial and industrial regions to have dust depositions rates below 1200mg/m²/day. Further investigations and remediation are required in areas with dust deposition rates between 1200mg/m²/day and 2400mg/m²/day. The areas recording concentrations above 2400mg/m²/day require immediate action and remediation.

Table 2.4 Dust standards, target, action and alert thresholds for dust deposition (SANS 1929:2011).

Level	Dust fall Rate(D) (mg/m²/day)	Average period	Permitted Frequency of Exceedances
Target	300	Annual	
Action residential	600	30 days	Three within any year, no two sequential months
Action industrial	1 200	30 days	Three within any year not sequential months
Alert threshold	2 400	30 days	None. first exceedance requires remediation and compulsory report to authorities

The PM_{10} standards issued nationally are documented in Table 2.4 and indicate the limit values, averaging periods and number of permissible exceedances.

Table 2.5 Limits for PM_{10} (SANS, 1929: 2011).

Average period	Concentration (µg/m³	Frequency of exceedances
24 h	75	4
1 year	40	0

Chapter 3

Materials and Methods

3.1 Introduction

In this study, the concentrations of different types of dust that were deposited at various dust monitoring points on the 8489-hectare property of the Khumani iron ore mine's (KIOM) were measured. The PM_{10} particle dust concentrations were also measured. These measurements were determined on a monthly basis for one year. Besides measuring the dust concentrations, the chemical composition of the fall-out dust was also determined. Lastly, several environmental parameters were studied to determine their influence on dust deposition.

The KIOM is located on the farms Bruce, King, Parsons and Mokaning, which lies 20 km south of Kathu and 65 km north of Postmasburg on the N14 in the Northern Province, South Africa (Figure 3.1). It is also located in close proximity of the well-known Si shen iron ore mine.

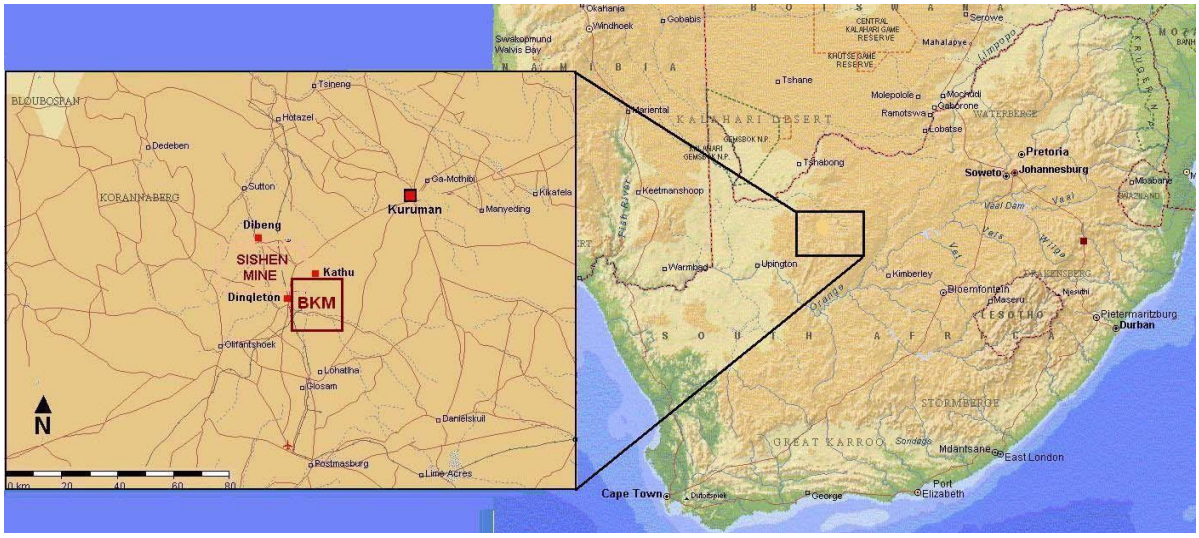


Figure 3.1 Location of KIOM near Kathu in the Northern Cape of South Africa.

(Gresse and Liebenberg-Enslin 2013)

3.2 Study design

This study was divided into different phases. The initial phase comprised of scouting the mining area to identify and select dust monitoring points. After identifying the different dust monitoring points, the dust monitoring buckets were erected. Dust was collected monthly and analysed according to standard methods (Figure 3.2).

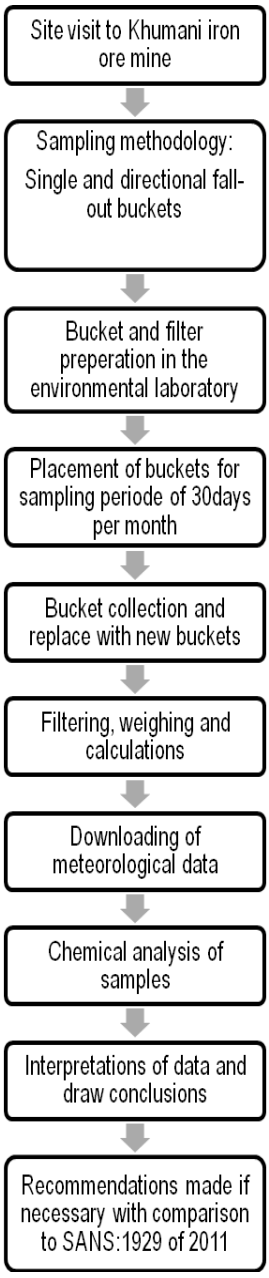


Figure 3.2 Study design for characterising dust in the vicinity of the KIOM.

3.3 Fall-out concentration measurement

Wind blows dust from a source into the air, and depending on the particle size, the wind speed and direction, the dust settles at different distances from the dust generating source (Kuhn and Loans 2013). In this study, dust generated from different sources on the mining property of the KIOM property was monitored. The different monitoring stations were positioned at strategic places on the mine property, taking into account the mining operations and future expansions. Fall-out dust was monitored by using two different fall-out dust monitoring systems. These systems were the single dust bucket (SDB) monitoring system and the multi-directional dust bucket (MDB) monitoring system (Figure 3.3). PM_{10} dust (particles smaller than 10 µm) monitoring was accomplished by using a calibrated deployable particulate sampler (DPS). Three PM_{10} dust monitoring points were established. Dust was collected and analysed from twelve fall-out dust bucket systems, of which eight stations were SDB monitoring systems and four were MDB monitoring systems.

a. b.

Figure 3.3 Fall-out dust buckets. a. Single dust bucket (SDB) monitoring system and b. Multi-directional dust bucket (MDB) monitoring system.

3.3.1 Preparation of dust buckets

For this study, a SDB monitoring system and a MDB monitoring system were set up in an attempt to compare their dust concentrations. Eight SDBs were prepared for dust collection. SDBs collect fall-out dust from all wind directions. On the other hand, four MDBs were prepared for dust collection. MDBs collect fall-out dust in four separate buckets. This multi dust sampling system was developed by Dust Watch and collects fall-out dust from the four main wind directions; north, south, east, and west. Fall-out dust collected from the four MDBs units represent a total of total 16 separate dust buckets.

The dust buckets for the two dust monitoring systems were prepared in a similar manner. All the buckets in this study were polypropylene buckets with a height of 237 cm. The diameter at the inside edge of the lip of a bucket was 175 cm, while the outside diameter of the lip was 179.8 mm. Dust bucket were prepared indoors to avoid prior contamination with dust. All buckets were partially filled with de-ionised water, taking into account the evaporation rate that might occur, and the seasonal conditions. Five to 10ml of the inorganic biocide copper sulphate was added to each to bucket to prevent algae growth. Each bucket was covered with gauze to prevent contamination from birds and insects. While in transportation to a dust monitoring point a lid was placed on a dust bucket to avoid prior contamination with dust. After the dust bucket were prepared, they were transported to the dust monitoring sites, the lid removed, placed in their respective cradles and left for 30 days. The dust monitoring buckets were visited regularly to check the water levels.

3.3.2 Fall-out dust measurement

After the dust buckets had remained at the monitoring sites for 30 days, they were collected and sent to the laboratory. The lids of the dust buckets were kept on a bucket while the bucket was in the que for processing. At the laboratory the fall-out dust of each bucket was collected and weighed. The

conditions in the laboratory were also strictly monitored and maintained. Fall-out dust concentrations were measured in the following manner:

1. Sampling Munktell filter papers with diameter of 47 mm were weighed to a scale of 0.01 prior to filtering the dust from a dust bucket using a microbalance Citizen C×265.
2. The contents of each dust bucket were filtered through a Buchner funnel and fall-out dust filtering vacuum system.
3. Approximately 1000 ml of water (Purite de-ionised water) were used to flush all the dust collected in each dust bucket into the collection container of the Buchner funnel system.
4. A spatula and squirt bottle were used to remove dust in the buckets and to ensure that no residual dust remained.
5. After applying the vacuum, the dust was collected on the pre-weighed filter paper.
6. Once all the dust had been collected, the filter paper was placed on an evaporation dish and left to dry in a protected area for approximately 24 hours.
7. The dried filter paper was then weighed using the same scale that was used to weigh the filter paper.
8. The mass of the fall-out dust was calculated by subtracting the weight of the filter paper and recorded in an Excel Spread sheet.
9. Dust deposition rate was then calculated using the dust deposition rate equation:

   $D = D/A$ g/m^2/day

   Where: D = deposition rate in grams/square metre/day;

   A = collection area, the cross-sectional area describes as m^2; and

   W = mass collect in grams.
10. After a dust bucket had been processed, it was cleaned with soap and water and left to drip-dry before being prepared for a further round of dust collection.

The fall-out dust vacuum filtering system with Buchner funnels is show in Figure 3.4.

Figure 3.4 Fall-out dust vacuum filtering system with Buchner funnels.

3.4 Chemical analysis of fall-out dust

Once the fall-out dust measurements of the SDBs were completed, these filters were used to determine the chemical composition of the dust. The dried dust containing filter papers of the SDBs were appropriately labelled and sent to the accredited Biograde Laboratory Services in Pretoria for chemical analysis. Chemical analysis was based on EPA methods 3050B and 6020A (US-EPA, 2000). The chemical analysis was done on a list of 42 metal elements commonly determined for fall-out dust samples. These elements were: Silver (Ag); Aluminium (Al); Arsenic (As); Gold (Au); Barium (Ba); Beryllium (Be); Bismuth (Bi); Calcium (Ca); Cadmium (Cd); Cobalt (Co); Chromium (Cr); Copper (Cu); Iron (Fe); Mercury (Hg); Iridium (Ir); Potassium (K); Lanthanum (La); Lithium (Li); Magnesium (Mg); Manganese (Mn); Molybdenum (Mo); Phosphorus (P); Lead (Pb); Palladium (Pd); Platinum (Pt); Rhodium (Rh); Ruthenium (Ru); Sulfur (S); Antimony (Sb); Selenium (Se); Tin (Sn); Strontium (Sr); Tellurium (Te); Thorium (Th); Titanium (Ti); Thallium (Tl); Uranium (U); Vanadium (V); Zinc (Zn); and Zirconium (Zr).

3.5 PM_{10} particle concentration measurement

The PM_{10} monitoring was sampled over a 24-hour period, once a month for the year of the study period. It was done at three identified monitoring points by using a DPS system. A Leland legacy sampling pump, as well as an impact sampler with an inertial impactor designed to remove particles larger than 10 µm was used to separate off all particles larger than 10 µm. All unwanted particles are captured on a disposable oiled impaction disc that reduces particle bounce. Particles within the correct particle size range were collected on a 47-mm Munktell filter. This was achieved by applying the sample pump to the particle-laden air at a flow rate of 10L/min through an impactor to separate airborne particles according to their aerodynamic diameter. The mass determination of the PM_{10} particles was similar to the procedure used for fall-out dust. Conditions in the laboratory were also strictly monitored and maintained as was the case with the fall-out dust measurements.

PM_{10} dust concentrations were measured by strictly completing the below four steps.

1. Media preparation and installation were done using the following steps:

- Prepare the impaction discs and filters by means of opening the packages and laboratory-controlled weighing procedure.
- Disassemble the impactor.
- Insert the collection filter into the filter cassette.
- Press prepared impaction disc into the filter cassette.
- Reinsert filter cassette in the impactor.
- Reassemble impactor.

2. Sampling set up and calibration were completed in the following manner:

- Set up the sample pump and set the pump flow rate to 10L/min.
- Screw the calibration adapter onto the impactor.
- Use tubing with quick-connect to attach pump inlet to outlet of impactor. Use short tubing to connect inlet of calibration adapter to outlet of flow meter or calibrator to form a calibration train. Calibrate pump flow rate with flow meter. Record the flow rate. Reset accumulated data if required.
- Disconnect the flow meter or calibrator and remove the calibration adapter from the impactor. Remove calibration media and place new unexposed media in impactor if required.
- Mount the bracket at the desired location.
- Screw the impactor onto the mounting bracket.
- Screw the rain cover onto impactor.

3. The sampling was then conducted by:

- Turning on the pump and recording the pertinent data.
- Turning off the pump after the desired sample time has elapsed. Recording the pertinent information.
- Remove the rain cover, reinstate the calibration train, and verify the pump flow rate.

4. Sample removal and analysis was then done as the final step:

- Use quick-connect to detach tubing from pump.
- Disassemble the impactor.

- Remove the impaction disc.
- Remove the filter cassette, disassemble and remove the collection filter.
- Place the collection filter in an appropriate container for weighing and analysis.

3.6 Methodology to determine meteorological influences

Several meteorological parameters were monitored to ascertain their effect on dust deposition. Climate conditions and topography may cause fine particles to remain airborne for days or months and may be transported for vast distances from the source (Mohan 2015). The interaction between dust and wind is very complicated; however, the norm is to assume that dust levels are higher when wind speeds are higher. Wind direction can change with altitude, resulting in ground level dust being blown in a separate direction when compared to dust blown in higher altitudes (Kuhn and Loans 2013). Another important meteorological parameter is precipitation. The meteorological station, EM-02-WXT weather station with Vaisala all-weather sensor, measures temperature, relative humidity, precipitation, hail, barometric pressure, as well as wind direction, wind speed, and wind gusts via a ultrasonic anemometer (Figure 3.4). Measurements of the respective meteorological parameters are recorded on a daily basis by the EM-02-WXT weather station.

Figure 3.5 Meteorological data station.

Summary statistics were produced for all meteorological parameters measured by the the EM-02-WXT weather station. For the analysis of the influence of wind speed and direction on dust deposition, wind roses were also produced from the wind data. A wind rose is a graphical tool that can be used to show wind speed and wind direction for a particular location over a specified period of time. A wind rose is usually divided into a number of spokes, which represent the frequency of winds blowing from in particular direction. Wind roses were produced for each month, as well as for the year. A classification system was developed to classify the wind patterns for a particular period, month or year. This system indicated the main direction(s) of the wind, uni-directional, bi- directional or multi-directional (Table 3.1).

Table 3.1 Classification of wind patterns.

Wind pattern	Icon	Description
Uni-directional		Wind blowing predominantly in one direction.

Bi-directional		Wind blowing predominantly in two directions.
Multi-directional		Wind blowing predominantly in more than two directions.

3.7 Data analysis

All data were recorded in Excel Spread Sheets (Excel 2016). Summary statistics were calculated for all measurement. Interventional statistics were applied to compare different groups of measurements. These tests included analyses of variance (ANOVA), Tukey's post hoc test and Pearson's correlation.

Chapter 4

Fall-out Dust Analysis at the Khumani Iron Ore Mine

4.1 Introduction

During the year of study, fall-out dust was collected on the premises of the KIOM. Monthly fall-out dust collections were made at 12 monitoring points, of which eight were single dust bucket (SDB) monitors and four multi-directional dust bucket (MDB) monitors. During the same period, particulate dust matter smaller than 10 µm (PM_{10}), was also collected monthly at three monitoring points.

Fall-out dust concentrations were determined for all dust sample collections. The sample concentration values were compared to the limit values of the South African National Standard 1929, ambient air quality limits for common pollutants (SANS 1929:2011). Additional to the measurement of fall-out dust concentrations, the sample filters collected from the SDBs were used for chemical analyses.

4.2 Fall-out dust

4.2.1 Single dust buckets

The SDB that were used to collect fall-out dust were located at different monitoring points on the premises of the KIOM. Five of the collection sites (SDB 3, 6, 7, 8, 15) were close to high dust-generating operational areas, whereas three (SDB 9, 13, 16) were placed near the mine's boundary, at a distance from high dust-generating operational areas. Figure 4.1 shows the positions of the eight SDB monitoring points and also shows the high dust-generating operational areas, such as the mining pits and mining dumps.

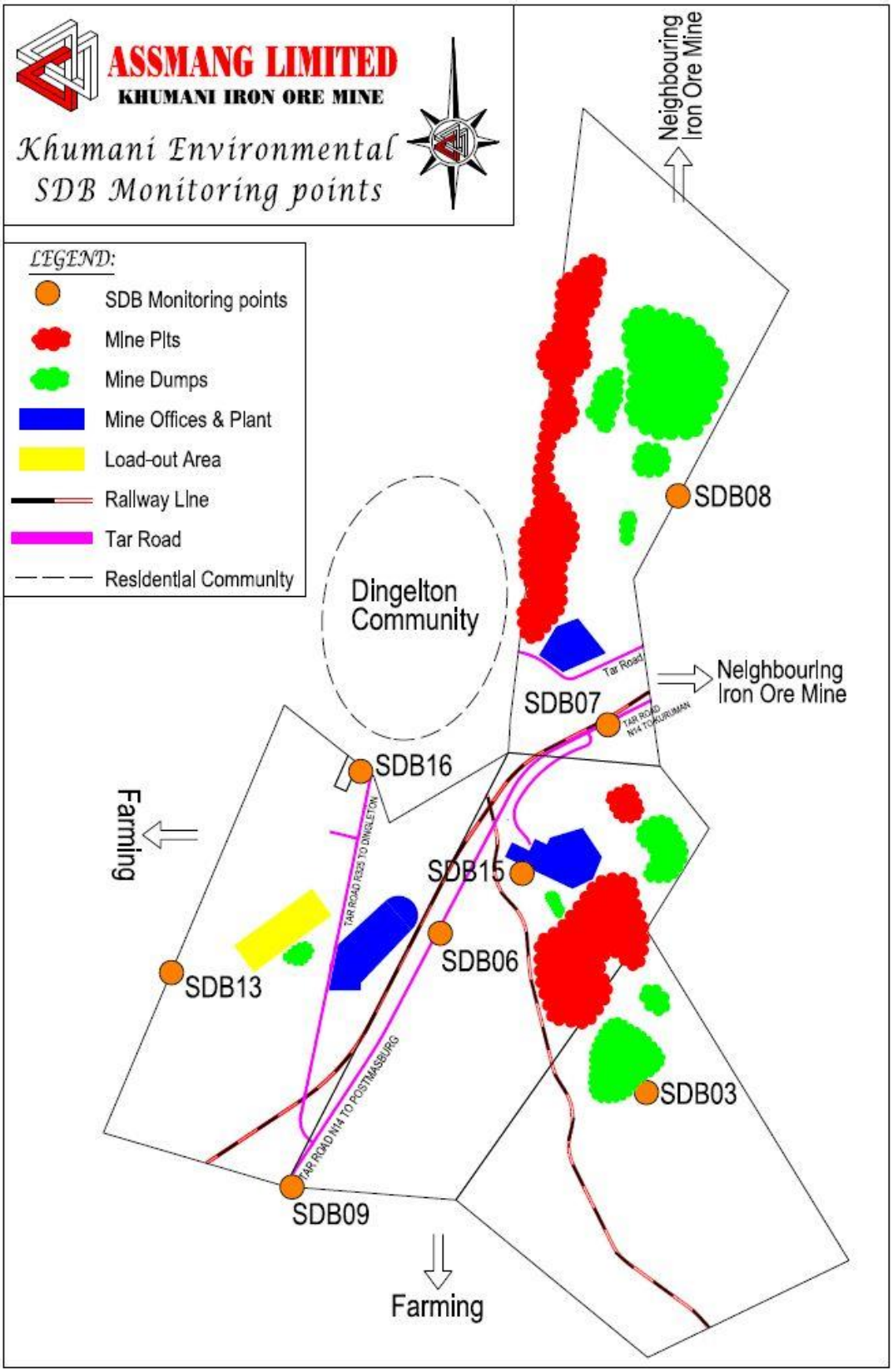


Figure 4.1 Map of KIOM showing the SDB monitoring points.

The two boundary monitoring points, SDB 9 and 13, demonstrated the lowest overall mean fall-out dust concentrations. In contrast, monitoring point SDB 15 that is surrounded by mining pits and dumps, showed the highest mean value of fall-out dust concentrations for the year (Table 4.1). The differences in fall-out dust concentrations at the respective monitoring points were demonstrated by the pronounced range (647.15) of mean values. When the fall-out dust concentration mean values of the individual months were compared, the highest mean value was recorded at monitoring point SDB 15 in August. This result could be attributed to the position of the monitoring point, which was surrounded by mining pits and dumps with a high dust-generating potential. Furthermore, during August it is usually very dry and windy, which was also the case during the year of study. The lowest fall-out dust concentration was recorded at the boundary monitoring point SDB 13 in April. This monitoring point was relatively further away from the dust-generating areas.

Table 4.1 Monthly SDB fall-out dust concentrations and summary statistics.

	Single dust bucket monitoring points							
Month	**3** (mg/m²/day)	**6** (mg/m²/day)	**7** (mg/m²/day)	**8** (mg/m²/day)	**9** (mg/m²/day)	**13** (mg/m²/day)	**15** (mg/m²/day)	**16** (mg/m²/day)
Jan	232.71	199.35	197.58	55.16	100.81	78.37	437.65	183.40
Feb	155.24	118.67	129.26	216.65	74.89	39.13	197.56	124.05
Mrt	160.98	183.57	202.90	178.81	127.27	119.66	740.58	167.35
Apr	198.49	184.72	165.59	139.55	38.06	34.26	497.87	34.30
May	62.58	143.03	195.40	270.91	60.37	42.61	558.47	110.39
June	170.46	206.32	151.49	61.16	67.89	53.80	879.79	99.19
July	177.32	264.58	146.48	543.78	52.05	49.48	956.08	127.05
Aug	146.95	322.73	250.13	191.23	61.90	63.32	1137.95	272.53
Sept	285.56	392.83	214.70	680.08	110.01	85.18	871.84	208.53
Oct	64.57	278.12	259.20	140.84	88.62	49.86	439.12	198.95
Nov	312.49	469.55	247.62	807.43	206.87	44.63	903.80	314.43
Dec	354.96	403.31	346.98	376.48	318.24	127.45	933.07	108.33
Mean	193.53	263.90	208.94	305.17	108.91	65.65	712.82	162.38

Month	Single dust bucket monitoring points							
	3 (mg/m²/day)	6 (mg/m²/day)	7 (mg/m²/day)	8 (mg/m²/day)	9 (mg/m²/day)	13 (mg/m²/day)	15 (mg/m²/day)	16 (mg/m²/day)
Min	64.57	118.67	129.26	55.16	38.06	34.26	197.56	34.3
Max	354.96	469.55	346.98	807.43	318.24	127.45	1137.95	314.43
SD	90.2057	111.9736	60.7414	246.6651	79.7103	31.0400	280.4193	78.5815

An analysis of variance (ANOVA) was performed to ascertain if significant differences in fall-out dust concentrations existed over the year at the different SDB monitoring points. The data revealed that the fall-out dust concentrations at the respective SDB monitoring points showed highly significant differences at $\alpha = 0.05$ (Table 4.2).

Table 4.2 ANOVA test results of SDB fall-out dust concentrations.

Source	SS	Df	MS	F	P
SDB (between)	3405911.28	7	486558.75	21.95	0.0001
Error (within)	1950687.60	88	22166.90		

Tukey's post hoc test was performed to ascertain at which SDB monitoring points the fall-out dust concentrations differed significantly from one another. The test revealed that the fall-out dust concentrations recorded at monitoring point SDB 15 differed significantly from the fall-out dust concentrations recorded at the other monitoring points. This could be attributed to the surrounding high dust-generating mining pits and dumps. Monitoring point SDB 8 displayed significant differences from two boundary monitoring points (SDB 9 and 13), as well as from the monitoring point (SDB 15) located in the highest dust-generating operational area.

Table 4.3 Tukey's post hoc test on SDB fall-out dust concentrations.

SDB monitoring point	3	6	7	8	9	13	15	16
3								
6	-							
7	-	-						
8	-	-	-					
9	-	-	-	★				
13	-	★	-	★	-			
15	★	★	★	★	★	★		
16	-	-	-	-	-	-	★	

★ = Statistically significant difference at $\alpha = 0.05$; - = not significant at $\alpha = 0.05$

A visual perspective of the monthly fall-out dust concentrations over the year provides a better understanding of the amounts of fall-out dust recorded at different times of the year. The two monitoring points, SDB 8 and 15, that demonstrated the greatest fluctuations are clearly visible in the graph (Figure 4.2). Both these monitoring points were located in high dust-generating operational areas. It appears as if the fall-out dust concentrations were generally higher during the dry and windy winter months of the year.

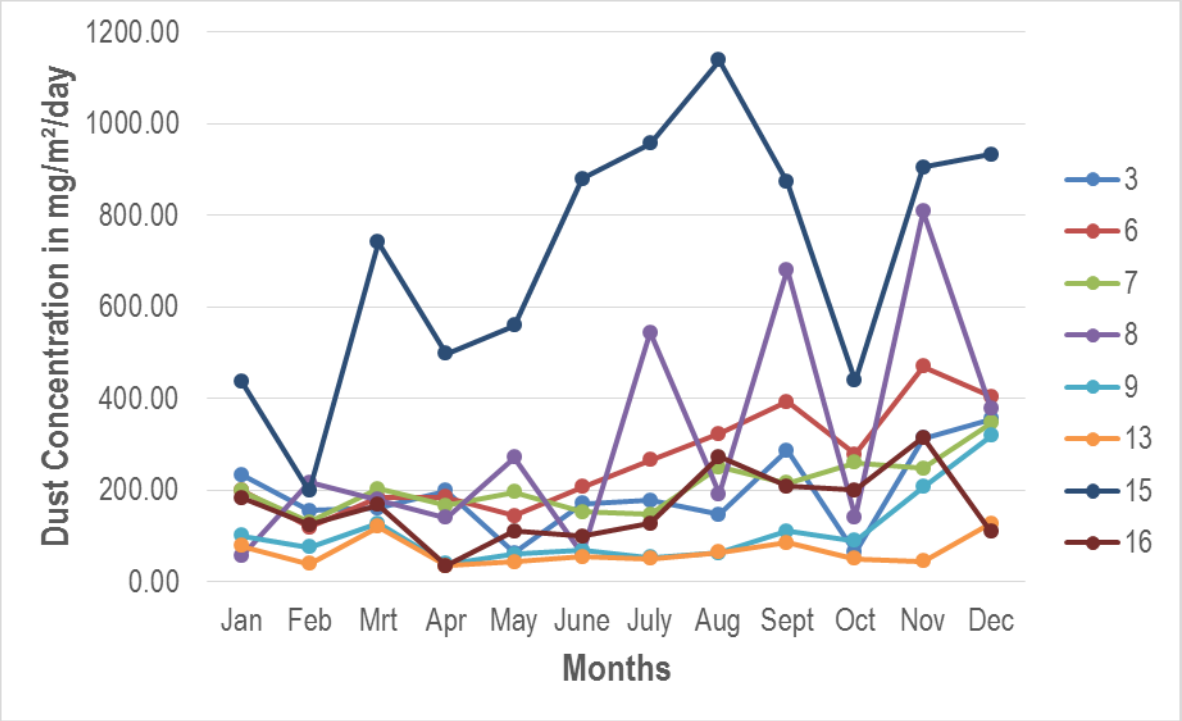


Figure 4.2 Fall-out dust concentrations over the year at the eight SDB monitoring points.

4.2.2 Multi-directional dust buckets

Multi-directional dust buckets (MDB) were used to collect fall-out dust at four monitoring points on the premises of the KIOM. Three of the monitoring points (MDB 11, 12, 14) were placed on the mine's boundary, which was at a distance from the dust-generating operational areas, whereas one monitoring point (MDB 2) was also located at a distance from the dust-generating operational areas, although not on the mine's boundary. Figure 4.3 shows the position of the MDB monitoring points, and also shows the high dust-generating operational areas, such as the mining pits and mining dumps.

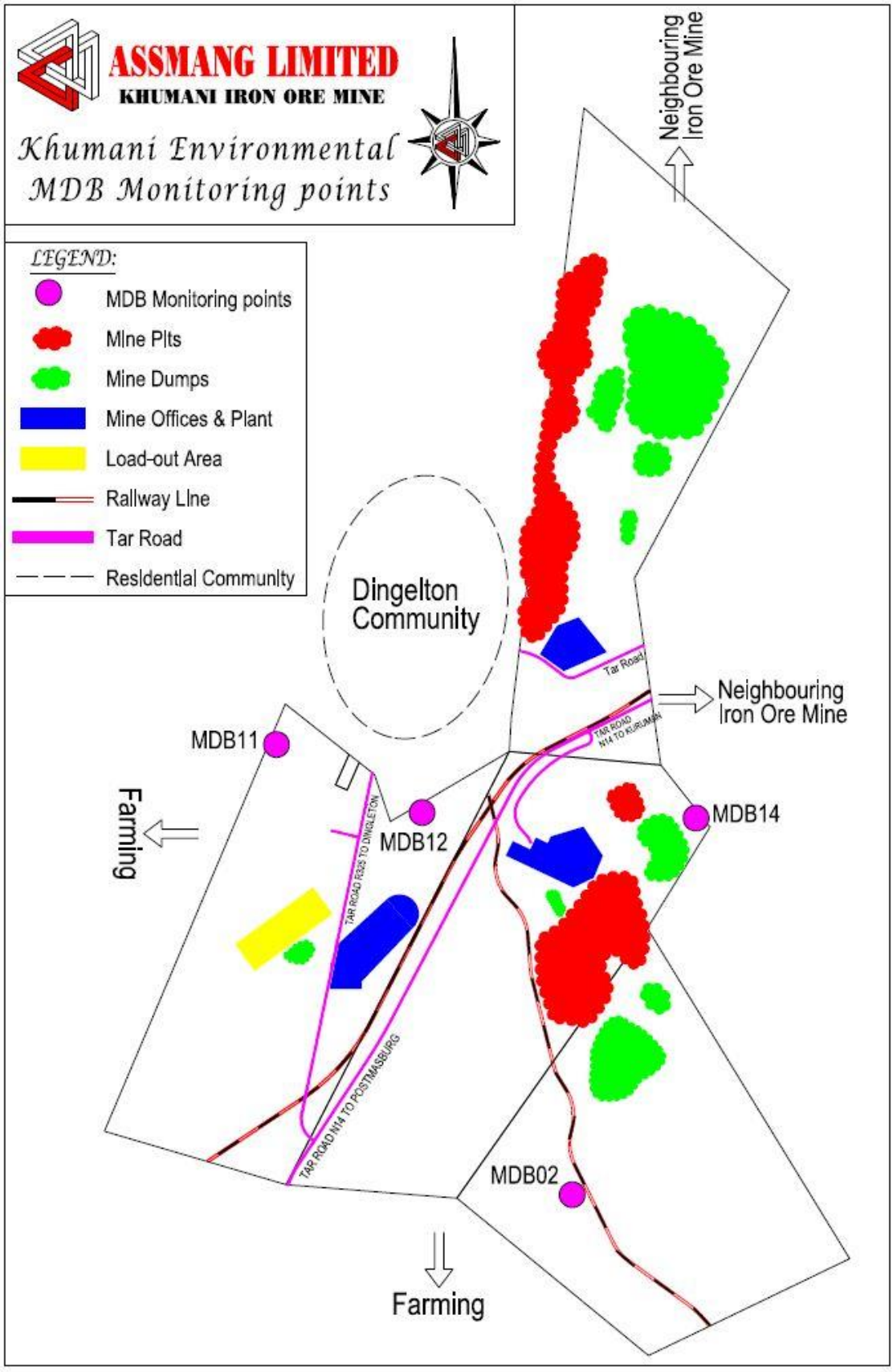


Figure 4.3 Map of KIOM showing the MDB monitoring points.

The MDB were used to ascertain to what extent wind direction influenced fall-out dust deposition. In each MDB, fall-out dust was collected in four separate buckets, each representing the four main wind directions. Of the four MDB monitoring points, the MDB monitoring point MDB 2 that was located approximately 1,000 metres from the mining pits and dumps, displayed the highest mean fall-out dust concentrations in all four wind directions (Table 4.4). Three of the highest fall-out dust concentrations were recorded in September for the southern, eastern and western dust buckets of MDB 2. In contrast, some of the lowest fall-out dust concentrations were recorded in April at MDB 2, with the eastern bucket showing the lowest fall-out dust concentration for the entire study. MDB 11, on the other hand, demonstrated the lowest mean fall-out dust concentrations in all four wind directional buckets. These lower fall-out dust concentrations can mostly be attributed to the position of MDB 11 at the boundary and the surrounding undisturbed, vegetated areas.

Table 4.4 Monthly MDB fall-out dust concentrations for northerly (N), southerly (S), easterly (E) and westerly (W) wind directions, and summary statistics.

Month	MDB 2 (mg/m²/day)				MDB 11 (mg/m²/day)				MDB 12 (mg/m²/day)				MDB 14 (mg/m²/day)			
	N	S	E	W	N	S	E	W	N	S	E	W	N	S	E	W
Jan	126.53	167.62	172.31	150.77	76.14	103.08	134.87	77.43	136.06	152.87	143.22	113.51	147.49	161.73	163.42	167.20
Feb	108.99	57.04	44.71	46.47	107.55	77.54	103.12	70.80	68.79	93.08	98.04	79.28	79.58	139.55	113.93	124.63
Mrt	74.39	109.33	75.18	84.59	91.59	98.33	154.36	100.56	77.06	147.81	127.72	110.75	122.12	48.05	132.57	114.40
Apr	40.03	45.50	31.70	35.20	39.71	38.47	84.61	53.76	86.42	112.96	109.75	71.49	111.23	87.03	95.12	53.52
May	64.44	49.67	43.33	42.42	64.54	74.74	106.25	84.58	82.90	85.45	85.29	62.95	59.59	59.03	106.93	105.06
June	203.78	337.87	195.15	207.43	60.51	87.80	58.24	56.72	131.89	137.50	174.18	80.38	92.33	94.53	93.72	58.18
July	148.00	161.16	114.32	112.03	62.64	77.26	61.03	62.68	116.29	275.68	168.10	186.86	181.16	264.93	180.25	149.26
Aug	480.77	830.94	518.93	632.76	86.17	108.14	75.49	51.25	442.67	443.03	316.50	273.54	145.41	237.77	311.81	217.43
Sept	578.42	1875.73	1781.30	1599.57	107.93	133.14	95.13	98.05	225.55	238.81	217.54	199.80	207.68	243.49	310.06	253.88
Oct	974.37	757.93	651.49	680.13	60.07	81.67	59.91	66.35	52.75	88.58	211.12	88.54	84.68	145.50	121.34	93.54
Nov	423.84	462.98	272.23	425.08	119.05	164.28	129.22	159.35	286.77	224.68	265.08	264.32	136.75	267.58	250.96	144.08
Dec	500.61	745.52	477.17	605.53	44.35	191.88	126.32	132.39	250.05	330.14	303.37	278.95	246.92	307.63	316.41	185.94
Mean	310.35	466.78	364.82	385.16	76.69	103.03	99.05	84.49	163.10	194.21	184.99	150.86	134.58	171.40	183.04	138.93
Min	40.03	45.5	31.7	35.2	39.71	38.47	58.24	51.25	52.75	85.45	85.29	62.95	79.58	59.03	93.72	53.52
Max	974.37	1875.73	1781.3	1599.57	107.55	191.88	134.87	159.35	442.67	443.03	303.37	278.95	246.92	307.63	316.41	253.88
SD	284.7926	533.1601	492.0109	455.2121	25.8169	42.1799	32.3146	33.3079	116.6191	111.5348	78.6544	84.7613	55.6325	89.8519	89.5154	60.5629

An ANOVA was performed to ascertain if significant differences in fall-out dust concentrations existed amongst the fall-out dust concentrations of the different wind directional buckets at each monitoring point. The tests revealed that the fall-out dust concentrations of the different directional buckets at the different MDB monitoring points did not reveal significant differences at $\alpha = 0.05$ (Table 4.5).

Table 4.5 ANOVA test results of the wind directional fall-out dust collections of the MDB.

MDB 2:

Source	SS	Df	MS	F	P
MDB (between)	151509.20	3	50503.07	0.25	0.8609
Error (within)	8961251.57	44	203664.81		

MDB 11:

Source	SS	Df	MS	F	P
MDB (between)	5477.30	3	1825.77	1.59	0.2053
Error (within)	50591.70	44	1149.81		

MDB 12:

Source	SS	Df	MS	F	P
MDB (between)	14179.17	3	4726.37	0.48	0.6978
Error (within)	433514.95	44	9852.61		

MDB 14:

Source	SS	Df	MS	F	P
MDB (between)	20580.47	3	6860.16	1.2	0.3208
Error (within)	251341.00	44	5712.30		

Because the fall-out dust concentration values of the different wind directional buckets at each of the MDB monitoring points did not reveal significant differences, the four fall-out dust concentration values of the directional buckets were massed. The massed data clearly showed that monitoring point MDB 2, which was located close to the mine pits and dumps, showed the highest mean fall-out dust concentrations, while monitoring point MDB 11, located on the north western boundary, showed the lowest fall-out dust concentrations of the four MDB (Table 4.6).

Table 4.6 Monthly massed MDB fall-out concentrations and summary statistics.

Month	MDB 2 (mg/m²/day)	MDB 11 (mg/m²/day)	MDB 12 (mg/m²/day)	MDB 14 (mg/m²/day)
Jan	617.23	391.52	545.65	639.84
Feb	257.21	359.02	339.19	457.69
Mrt	343.50	444.84	463.33	417.13
Apr	152.43	216.54	380.62	346.89
May	199.86	330.10	316.59	330.62
June	944.24	263.26	523.94	338.76
July	535.51	263.61	746.93	775.60
Aug	2463.40	321.05	1475.74	912.42
Sept	5835.03	434.26	881.69	1015.12
Oct	3063.92	268.00	440.98	445.06
Nov	1584.13	571.90	1040.86	799.37
Dec	2328.83	494.95	1162.51	1056.89
Mean	1527.11	363.25	693.17	627.95
Min	152.43	216.54	316.59	330.62
Max	5835.03	571.90	1475.74	1056.89
SD	1685.73	107.36	372.17	273.70

An ANOVA was performed to ascertain if significant differences in fall-out dust concentrations existed amongst the respective MDB monitoring points. The ANOVA test revealed that the dust concentrations of the massed fall-out dust concentrations at the different MDB monitoring points did not differ significantly at $\alpha = 0.05$ (Table 4.7).

Table 4.7 ANOVA test results of MDB massed fall-out dust concentrations.

Source	SS	Df	MS	F	P
MDB (between)	151509.20	3	50503.07	0.25	0.860901
Error (within)	8961251.57	44	203664.81		

A visual perspective of the monthly massed fall-out dust concentrations of the MDB monitoring points over the year provides a better understanding of the concentrations of fall-out dust at different times of the year. For the most, the fall-out dust concentrations were similar throughout the year at the different MDB monitoring points (Figure 4.4). The exception was MDB 2 that showed a marked increase in fall-out dust during the dry month of September. This increase could be explained by the intensive construction work on a railway line extension that started during August. This MDB monitoring point is located next to the road used by the construction vehicles, and therefore explains the sharp increase in fall-out dust concentrations. Furthermore, these high fall-out dust concentrations were recorded prior to the commencement of the rainy season and thus the presence of dry airborne particulates in the environment.

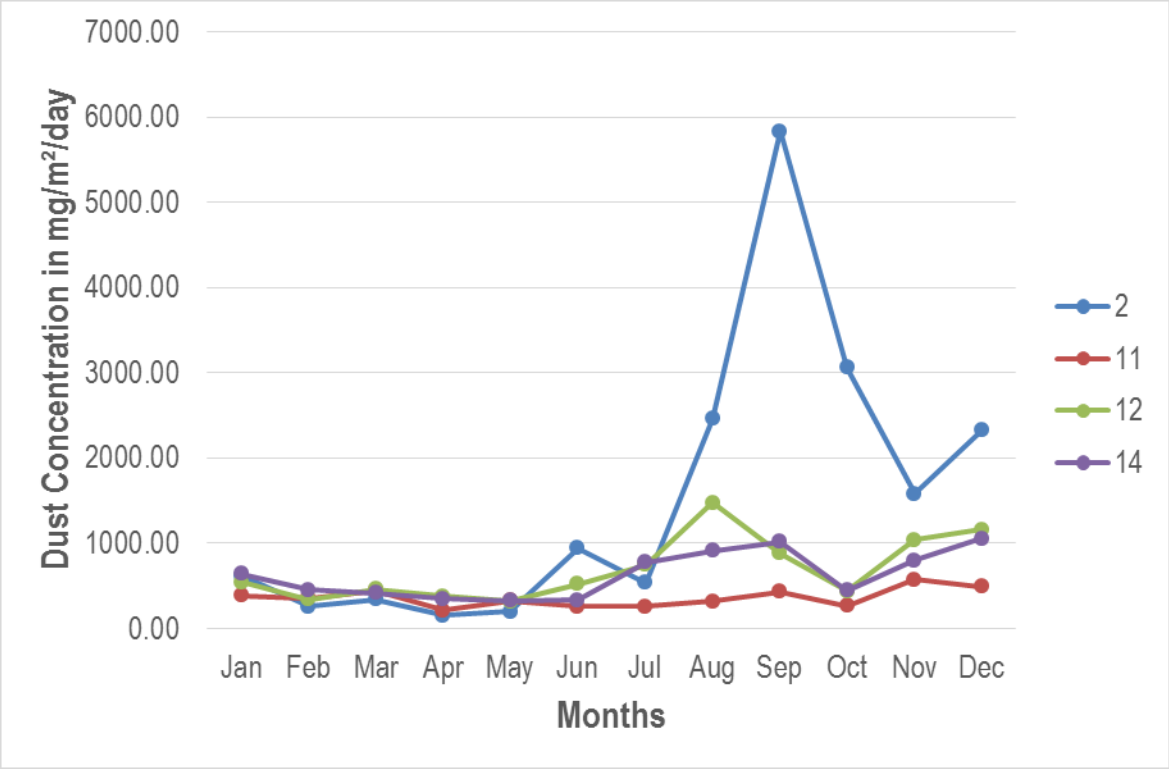


Figure 4.4 Massed fall-out dust concentrations over the year at the four MDB monitoring points.

4.3 PM_{10} dust

During the year, dust was collected from three PM_{10} dust monitoring points on the premises of the KIOM. Two of the PM_{10} dust monitoring points, King South and Hoffman, were placed on the mine's boundary, at a distance from the dust-generating operational areas. The third monitoring point, Markram, was located near the dust-generating operational plant area. Figure 4.5 shows the position of the PM_{10} dust monitoring points as well as the high dust-generating operational areas, such as the mining pits and mining dumps.

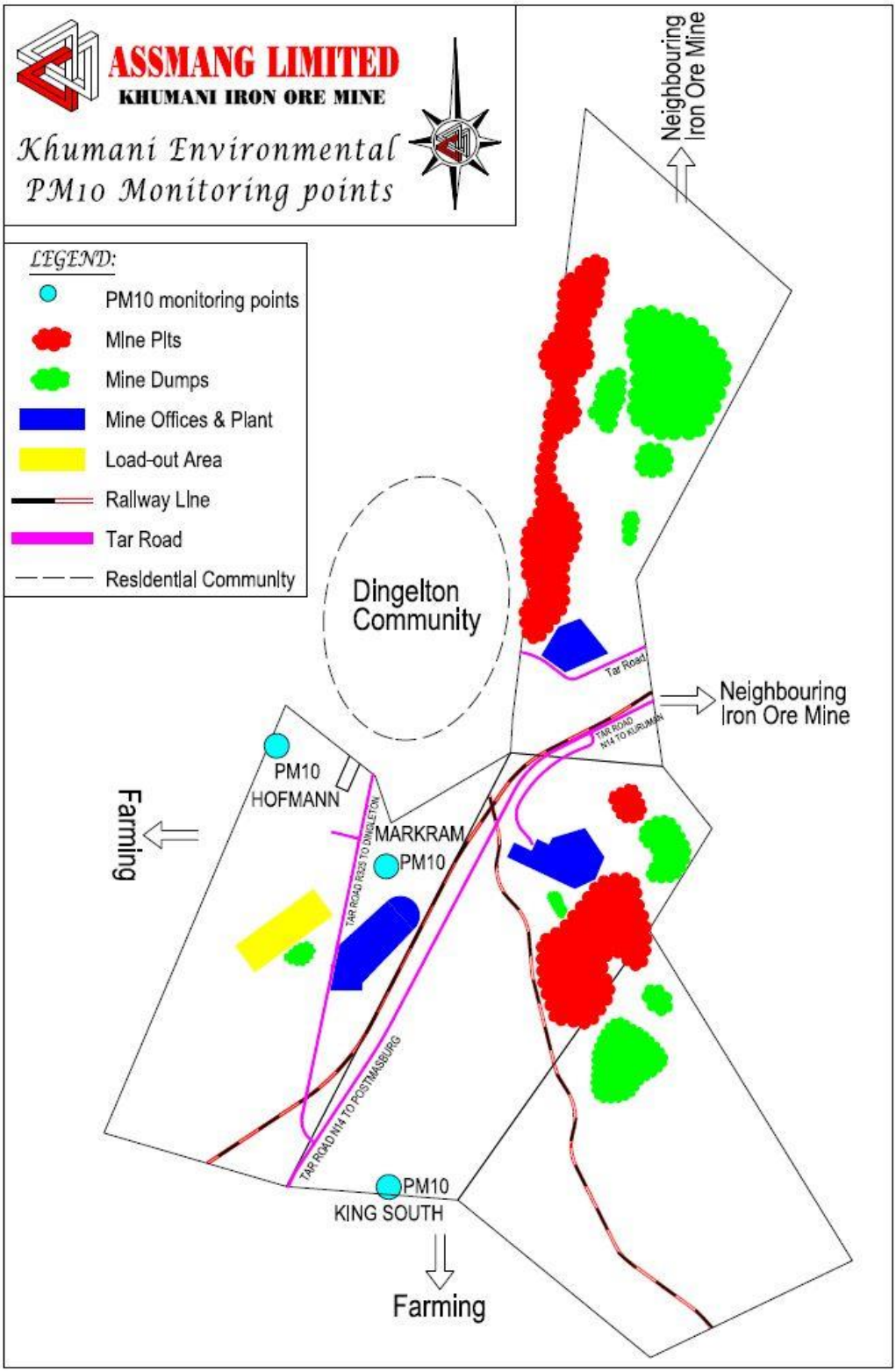


Figure 4.5 Map of KIOM showing the PM_{10} dust monitoring points.

The PM_{10} dust concentrations appeared to be comparable for all three PM_{10} dust monitoring points. These data thus revealed that there were no marked differences in PM_{10} dust concentrations at monitoring points (King South and Hoffman) at a distance from dust-generating operational areas and at a dust monitoring point (Markram) in the dust-generating operational area (Table 4.8).

Table 4.8 Monthly PM_{10} dust concentrations and summary statistics.

Months	King South (µg/m³)	Hoffman (µg/m³)	Markram (µg/m³)
Jan	25.38	30.01	34.15
Feb	31.70	31.74	30.74
Mar	28.54	29.51	37.63
Apr	28.30	33.66	30.39
May	29.43	30.52	33.51
Jun	30.42	30.09	31.12
July	30.97	31.42	29.86
Aug	25.55	24.42	30.57
Sept	30.01	28.04	29.88
Oct	31.04	31.32	29.76
Nov	28.99	27.33	32.43
Dec	31.27	27.10	31.25
Mean	29.30	29.60	31.77
Min	25.38	24.42	29.76
Max	31.70	31.74	37.63
SD	2.09	2.51	2.33

An ANOVA was performed to ascertain if significant differences existed amongst the PM_{10} dust concentrations at the different PM_{10} dust monitoring points. The ANOVA revealed that the PM_{10} dust concentrations did differ significantly at $\alpha = 0.05$ (Table 4.9). A Tukey's post hoc test revealed that the measurements of King South differed significantly from the measurements taken at Markram.

Table 4.9 ANOVA test results of PM_{10} dust concentrations.

Source	SS	Df	MS	F	P
PM_{10} point (between)	43.80	2	21.90	4.07	0.026310
Error (within)	177.43	33	5.38		

A visual perspective of the monthly PM_{10} dust concentrations over the year at the three monitoring points provides a better understanding of the monthly variation in concentrations. The Markram monitoring point, located in the dust-generating operational area, demonstrated the highest readings during eight months of the year (Figure 4.6).

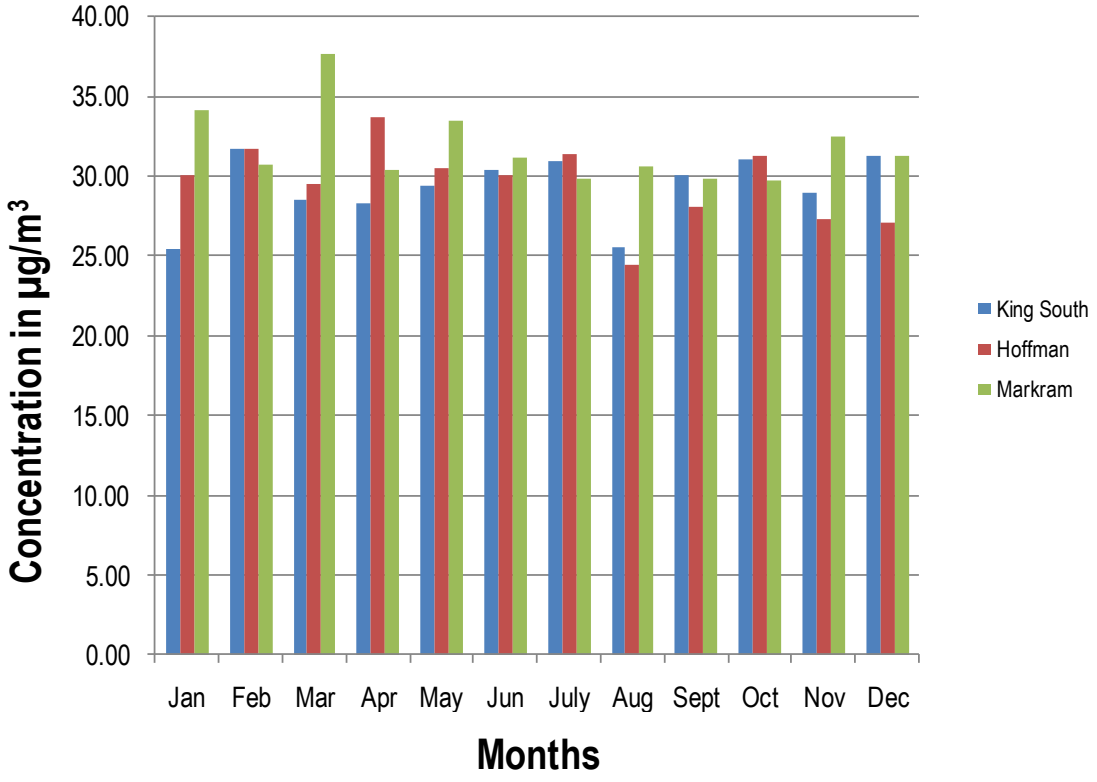


Figure 4.6 Histogram of the total monthly PM_{10} dust concentrations at the three PM_{10} dust monitoring points.

4.4 Comparison of different classes of fall-out dust

The data revealed that the concentrations of fall-out dust of the different categories varied substantially over the year. In an attempt to compare the different categories, the mean dust concentrations of the SDB, MDB and PM_{10} were plotted (Figure 4.7). The graph shows that during the months of August and September the dust load was high for both SDB and the massed MDB concentrations. It further indicates that the dust loads of SDBs and MDBs were substantially less during the first few months of the year when compared to August and September. The fluctuation of the PM_{10} concentrations was relatively low, although in August a drop in the PM_{10} load was noted.

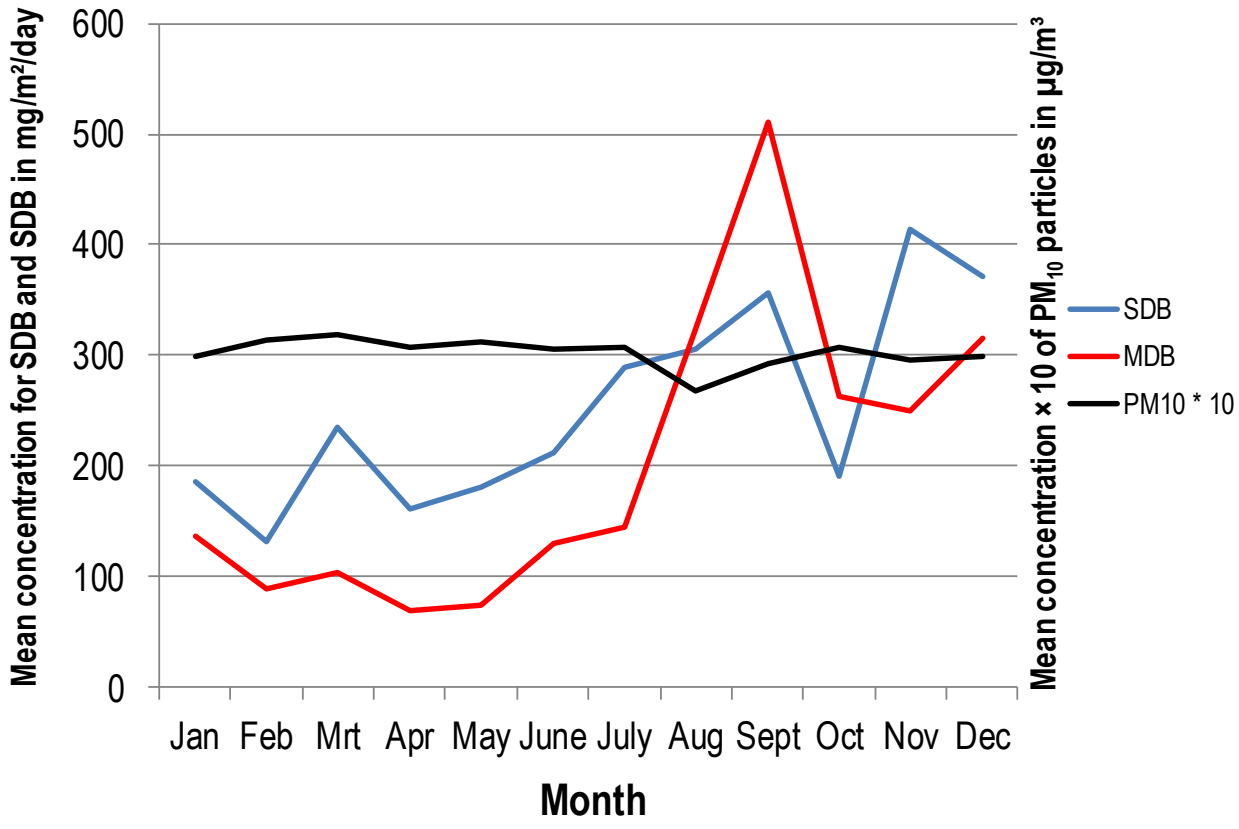


Figure 4.7 Dust concentrations of SDB, MDB and PM_{10} for the 12 months of the study year.

4.5 Chemical analysis of fall-out dust

The fall-out dust collections made over the year at the respective SDB and MDB dust monitoring points were analysed for a total of 42 chemical elements. The concentrations of 17 of the 42 chemical elements were below detectable limits (BDL), which were values less than 0.0001 mg/kg. Therefore, these chemical elements were excluded from the list of 42 chemical elements, thereby reducing the number of chemical elements to 25. Of the remaining 25 chemical elements, occupational exposure limits (OEL) could be

sourced for 12 of these chemical elements. The measurements of these 12 chemical elements were then compared to OEL, as well as to environmental exposure limit (EEL). The EELs were included in this study because they gave some idea of the potential health risks with continuous exposure to these chemical elements to the general public. The EEL were calculated as one fortieth of the OEL (Schoeman and Van den Heever 2014). Before any comparisons could be made, the recorded measurement values in mg/kg were first converted to mg/m³ air, which are the units of the OEL.

The concentrations of the chemical elements were for the most within both OEL and EEL. However, the results did show that the three elements barium, copper and iron demonstrated noticeably higher concentrations than the other elements (Table 4.10). The concentrations of copper and iron exceeded both the OEL and EEL at all the dust monitoring points. Barium, on the other hand, exceeded the EEL at all the dust monitoring points, while the concentrations at only two of the dust monitoring points exceeded the OEL.

Table 4.10 Chemical analysis for the SDB and the massed MDB fall-out dust samples.

Element	OEL	EEL	SDB and MDB fall-out dust monitoring points											
			2	3	6	7	8	9	11	12	13	14	15	16
Al	2.0000	0.0500	0.6700	1.5400	0.9300	0.9900	0.6300	0.7400	0.7300	1.1900	0.6700	0.7700	1.7700	1.1800
As	0.1000	0.0025	0.0028	0.0049	0.0043	0.0052	0.0040	0.0034	0.0025	0.0034	0.0021	0.0021	0.0071	0.0023
Ba	0.5000	0.0125	0.1500	**0.8800**	0.3900	**0.5900**	0.4600	0.1600	0.1800	0.3900	0.1400	0.4200	0.4200	0.2700
Cr	0.5000	0.0125	0.0200	0.0143	0.0183	0.0104	0.0057	0.0217	0.0053	0.0083	0.0062	0.0083	0.0187	0.0153
Co	0.1000	0.0025	0.0048	0.0063	0.0087	0.0058	0.0022	0.0034	0.0041	0.0063	0.0027	0.0036	0.0137	0.0072
Cu	0.2000	0.0050	**6.0500**	**0.6900**	**9.9900**	**2.5600**	**1.2600**	**4.8100**	**0.3500**	**2.5400**	**0.3400**	**1.5700**	**1.0800**	**6.3800**
Fe	1.0000	0.0250	**3.0600**	**8.8700**	**4.5400**	**5.3700**	**2.5600**	**3.2100**	**3.2700**	**5.2100**	**3.1300**	**3.6700**	**13.7800**	**5.2200**
Mn	5.0000	0.1250	0.4000	2.5500	0.6200	1.2700	0.4800	0.5300	0.7100	0.8400	0.5300	1.0000	2.3400	0.5900
Hg	0.0100	0.0003	0.0025	0.0016	0.0025	0.0016	0.0008	0.0016	0.0008	0.0016	0.0008	0.0008	0.0016	0.0016
Ni	1.0000	0.0250	0.0086	0.0149	0.0072	0.0139	0.0082	0.0089	0.0108	0.0125	0.0091	0.0113	0.0122	0.0065
Sn	0.1000	0.0025	0.0228	0.0146	0.0092	0.0189	0.0374	0.0214	0.0185	0.0073	0.0175	0.0185	0.0107	0.0214
Zn	5.0000	0.1250	0.0030	0.0097	0.0045	0.0060	0.0037	0.0034	0.0034	0.0056	0.0037	0.0045	0.0134	0.0060

OEL = occupational exposure limits; EEL = environmental threshold limit values

4.6 Discussion

Although there are numerous natural and anthropogenic sources of atmospheric particulates, mining operations pose the greatest potential risk to human health and the environment (Csavina *et al.* 2012). Mining operations generate notable quantities of dust as was revealed in this study. Thus, the workforce of KIOM may be exposed to large quantities of fall-out dust, as well as smaller particulate dust matter, such as PM_{10} particulate dust matter and smaller.

Mining dust is commonly associated with significantly elevated levels of one or more chemical element (Meza-Figueroa *et al.* 2009; Brotons *et al.* 2010; Csavina *et al.* 2012). This study revealed that iron and copper exceeded both the OEL and EEL. The high atmospheric levels of these metal-bearing atmospheric particulates can have a substantial impact on the health of the workforce and the environment (Berico *et al.* 1997; Soukup *et al.* 2000; Ghio and Devlin 2001; WHO 2003). Several studies have indicated that lung cancer is a common disease among workers who are exposed to iron ore dust (Boyd *et al.* 1970; Kinlen and Willows 1988; Chau *et al.* 1993; Wild *et al.* 2009). Accumulation of iron in the brain results in decreased brain function due to illness such as Parkinson's and Alzheimer's disease (Quintana *et al.* 2006). Furthermore, pneumoconiosis may also result from inhalation of iron dust (Nemery 1990). Copper-bearing dust can affect the human body if inhaled or if they come in contact with eyes or skin. In the short term, copper may cause a feeling of illness similar to the common cold with sensations of chills and stuffiness of the head. Small copper-bearing particles may enter eyes and cause irritation and damage. Long-term exposure could cause skin irritation or discolouration of the skin and hair (Agency for Toxic Substances and Disease Registry 2004).

Dust particle size affects dust deposition efficiency in the human respiratory system upon inhalation. Coarse particles, such as fall-out dust is deposited in the upper respiratory system, swallowed, goes through the digestive system and may be absorbed, depending on their bioavailability. In contrast,

fine particles, such as PM_{10} and smaller particulate dust matter may be respired deep into the lungs where they can be transported directly to the blood stream (Krombach *et al*. 1997; Park and Wexler 2008; Valiulis *et al*. 2008).

The role of mining activities may become more and more important in coming decades. Of particular importance is climate change and land use. Land use is destined to intensify and together with climate change can substantially increase the potential for dust emissions and (Csavina *et al*. 2012).

Chapter 5

Environmental Factors and Dust Deposition

5.1 Introduction

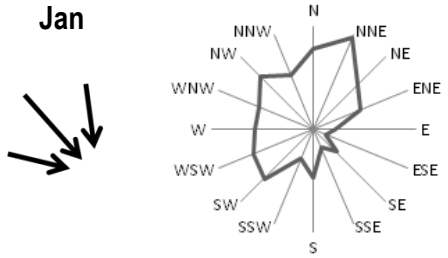
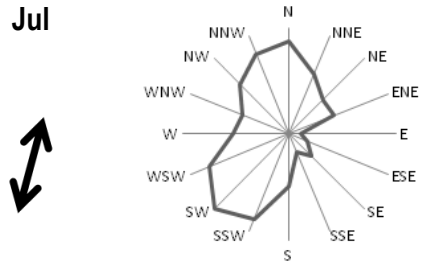
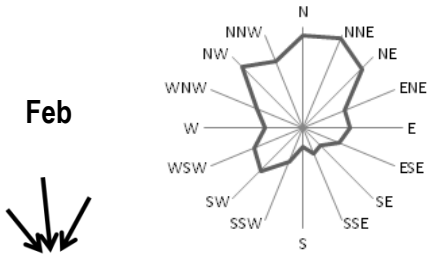
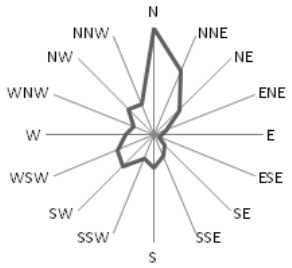
Besides particle size, dust deposition is also dependent upon prevalent weather conditions. Wind can transport suspended particles over a wide area. Smaller particles will remain suspended for longer periods, dispersing widely and depositing more slowly. Larger dust particles will be deposited more quickly. Particles over 30 µm make up the greater proportion of dust emitted from mining activities and will deposit within 100 m of the source. Intermediate sized particles (10–30 µm) will be able to travel up to 200–500 m. Particles smaller than 10 µm represent a small portion of dust emitted from most mining activities and are deposited slowly (Wentzel 2015). Wind speed determines the distance that dust particles travel, whereas wind direction determines the general path the dust particles will follow before settling. In the iron ore mining sector, it has been shown that the dust load is heavier around the dust-generating sources, such as the mine pits and dumps. Depending on the seasonal rainfall in an area, humidity also influences dust deposition (Kuhn and Loans 2013). Thus, wind direction, wind speed, particle size, particle weight and relative humidity can be used to predict the deposition of fall-out dust in certain areas (Alcoa World Alumina Australia 2007). Precipitation was excluded from this study, because the average rainfall during the year of study was negligible.

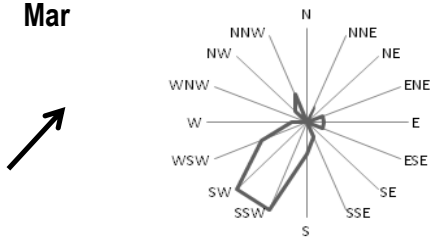
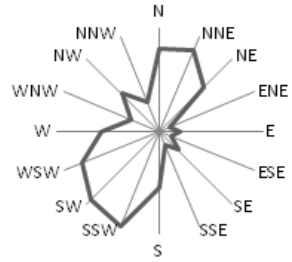
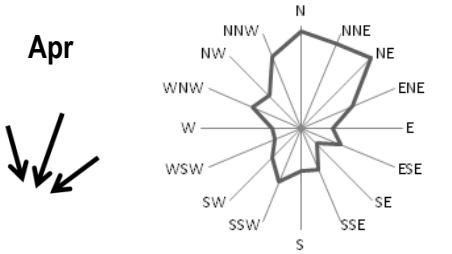
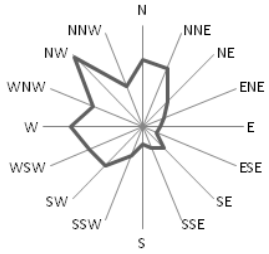
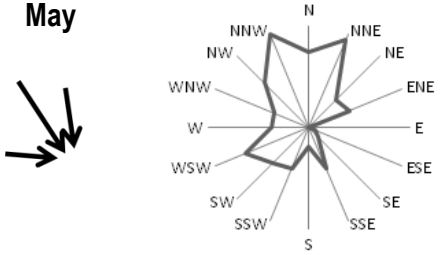
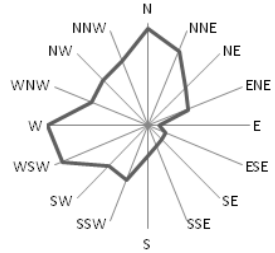
5.2 Environmental factors and dust deposition

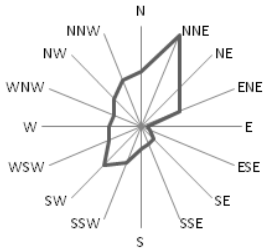
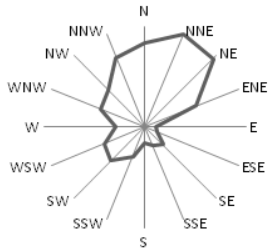
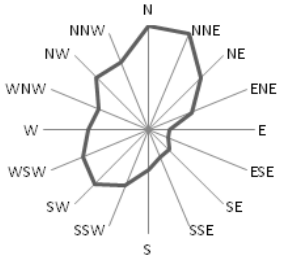
A wind rose is a graphical tool used to show wind speed and wind direction for a particular location over a specified period of time. A wind rose is divided into a number of spokes which represent the frequency of winds blowing from in particular direction. Yearly and monthly wind roses were constructed for mean total fall-out dust (SDB + MDB) and mean PM_{10} dust concentrations (Table

5.1). The mean total fall-out dust (SDB + massed MDB) was calculated to give a better understanding of the fall-out dust concentration over the whole mining area with the wind speed and direction taken into consideration. The mean total fall-out dust concentrations were calculated per month for SDB and MDB combined. For the majority of the months of the year the wind direction was either bi-directional or multi direction, mostly from a northerly direction. The predominating wind directions for the year of study were north (N), north north east (NNE) and south west (SW). Mean total fall-out dust concentrations were substantially higher from August until the end of the year when compared to the other months of the year. The highest mean total fall-out dust concentration was recorded in September when the predominant wind direction was SSW and NNE. August had the second highest mean total fall-out dust concentration when the wind was predominantly in a northerly. The lowest mean total fall-out dust concentration was recorded for April when the prevailing wind directions were mostly N, NNE and NE. The mean total PM_{10} particle concentration was calculated per month. Throughout the year of study these concentrations demonstrated relatively little variation; ranging from 26.85 µg/m³ in August 31.9 µg/m³ in March.

Table 5.1 Relationship between monthly and year prevailing wind direction and dust collection in total dust (MDB + SDB) and PM_{10}.

Month and description	Wind rose	Mean total fall-out dust ($mg/m^2/day$)	Mean total PM_{10} ($\mu g/m^3$)	Month and description	Wind rose	Mean total fall-out dust ($mg/m^2/day$)	Mean total PM_{10} ($\mu g/m^3$)
Jan		153.3	29.84	Jul		193.3	30.75
Feb		102.9	31.4	Aug		317.5	26.85

Month and description	Wind rose	Mean total fall-out dust (mg/m²/day)	Mean total PM_{10} (µg/m³)	Month and description	Wind rose	Mean total fall-out dust (mg/m²/day)	Mean total PM_{10} (µg/m³)
Mar		147.9	31.9	Sep		458.9	29.31
Apr		99.5	30.8	Oct		239.1	30.7
May		109.2	31.2	Nov		304.3	29.6

Month and description	Wind rose	Mean total fall-out dust (mg/m²/day)	Mean total PM_{10} (µg/m³)	Month and description	Wind rose	Mean total fall-out dust (mg/m²/day)	Mean total PM_{10} (µg/m³)
Jun		156.7	30.5	Dec		333.8	29.9
Year		218.0	30.2				

5.3 Correlation between environmental factors and dust concentration

5.3.1 Wind speed and dust concentration

Pearson's correlation coefficients were calculated for wind speed and the different types of dust concentrations to measure the strength and direction of the relationship between these variables. The correlation coefficient (R) indicated that fall-out dust concentration measurements for SDB, massed MDB, as well as total dust concentration (SDB + massed MDB), were positively correlated. MDB and total fall-out dust concentrations demonstrated strong relationships (Table 5.2). The R^2 values of the massed MDB and total fall-out revealed that approximately 60% of the variance could be explained by wind speed. In contrast, the correlation between wind speed and PM_{10} was moderate, but in an opposite direction when compared to the other dust variables.

Table 5.2 Coefficient of correlation and coefficient of determination for wind speed and dust concentration.

Variable pair	R	R^2	Explanation
Wind and SDB dust concentration	0.7054	0.4976	Moderate positive correlation.
Wind and MDB dust concentration	0.7706	0.5938	Strong positive correlation.
Wind total dust concentration	0.7978	0.6365	Strong positive correlation.
Wind PM_{10} concentration	-0.7309	0.5342	Moderate negative correlation.

R= coefficient of correlation; R^2=coefficient of determination

Scatter plots were constructed to demonstrate the relationships between wind speed and the types of dust concentrations. The regression lines on the plots in Figure 5.1 show clearly the positive relationship between wind speed and SDB, MDB and total dust concentrations of fall-out dust. The negative relationship between wind speed and PM_{10} is also clearly depicted.

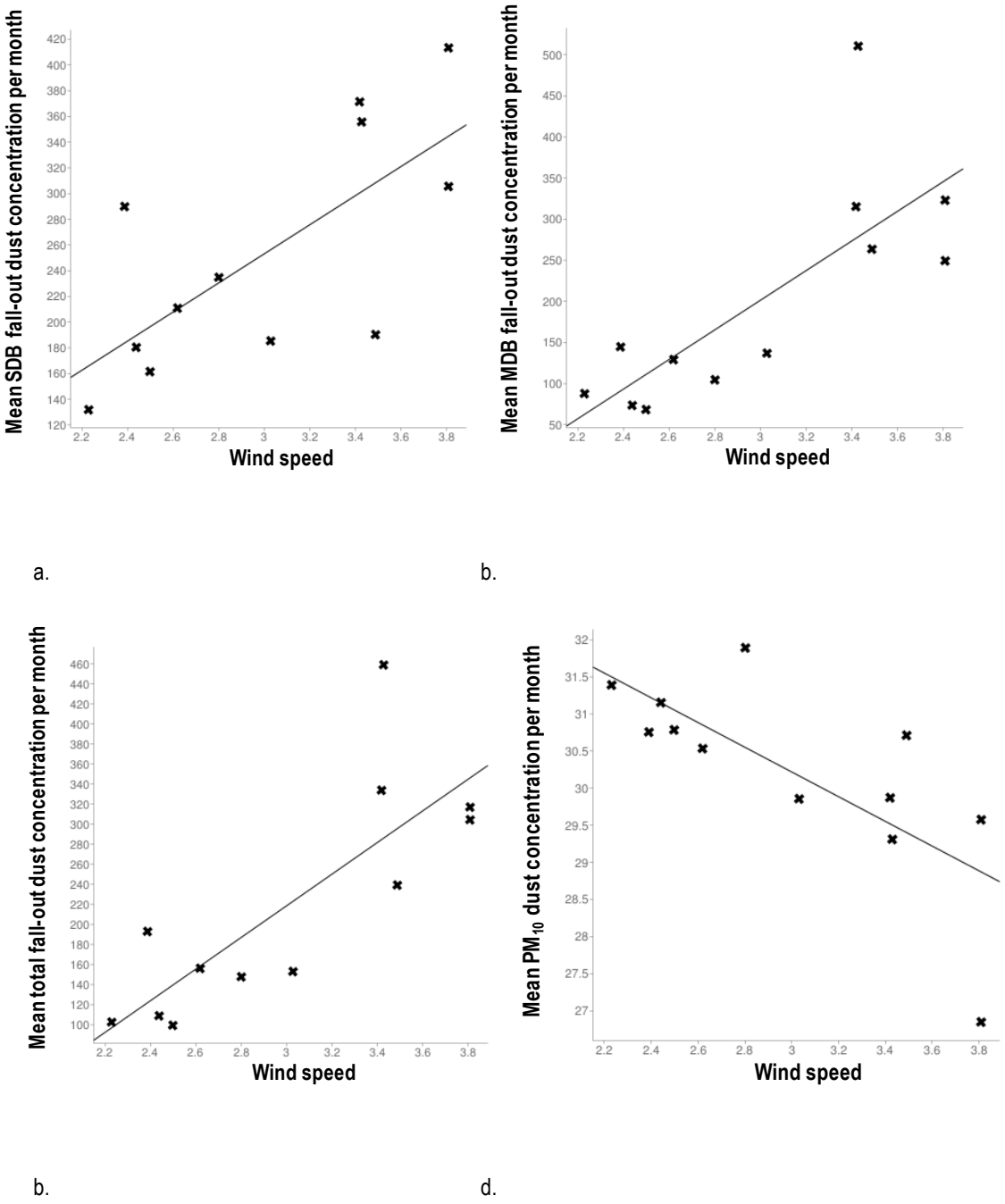


Figure 5.1 Scatter plots and regression lines for wind speed and dust concentration. (a) SDB dust concentration, (b) massed MDB dust concentration, (c) Total dust concentration, and (d) PM_{10} particle concentration.

5.3.2 Relative humidity speed and dust concentration

Pearson's correlation coefficients were calculated for relative humidity and the different types of dust concentrations to measure the strength and direction of the relationship between these variables. In contrast to the correlation coefficients that were determined for wind speed, the correlation coefficients for relative humidity with SDB, massed MDB, as well as total dust concentration (SDB + massed MDB), were negatively correlated (Table 5.3). All three these correlation coefficients were moderate to weak. For PM_{10}, the correlation coefficient with relative humidly was weak and negative. The R^2 values were low for all four pairs of analyses.

Table 5.3 Coefficient of correlation and coefficient of determination for humidity and dust concentration.

Variable pair	R	R^2	Explanation
Humidity and SDB dust concentration	-0.4341	0.1884	Although technically a negative correlation, the relationship is only weak.
Humidity and MDB dust concentration	-0.5574	0.3107	Moderate negative correlation.
Humidity total dust concentration	-0.5566	0.3098	Moderate negative correlation.
Humidity and PM_{10} concentration	0.3817	0.1457	Although technically a positive correlation, the relationship is only is weak.

R= coefficient of correlation; R^2=coefficient of determination

Scatter plots were constructed to demonstrate the relationships between relative humidity and the types of dust concentrations. Although regression lines on the plots in Figure 5.2 show negative relationships between relative humidity and SDB, MDB and total dust concentrations, the spread of the data points indicate the relatively weak relationships. Similarly, the weak positive relationship was probably strongly influenced by the outlier.

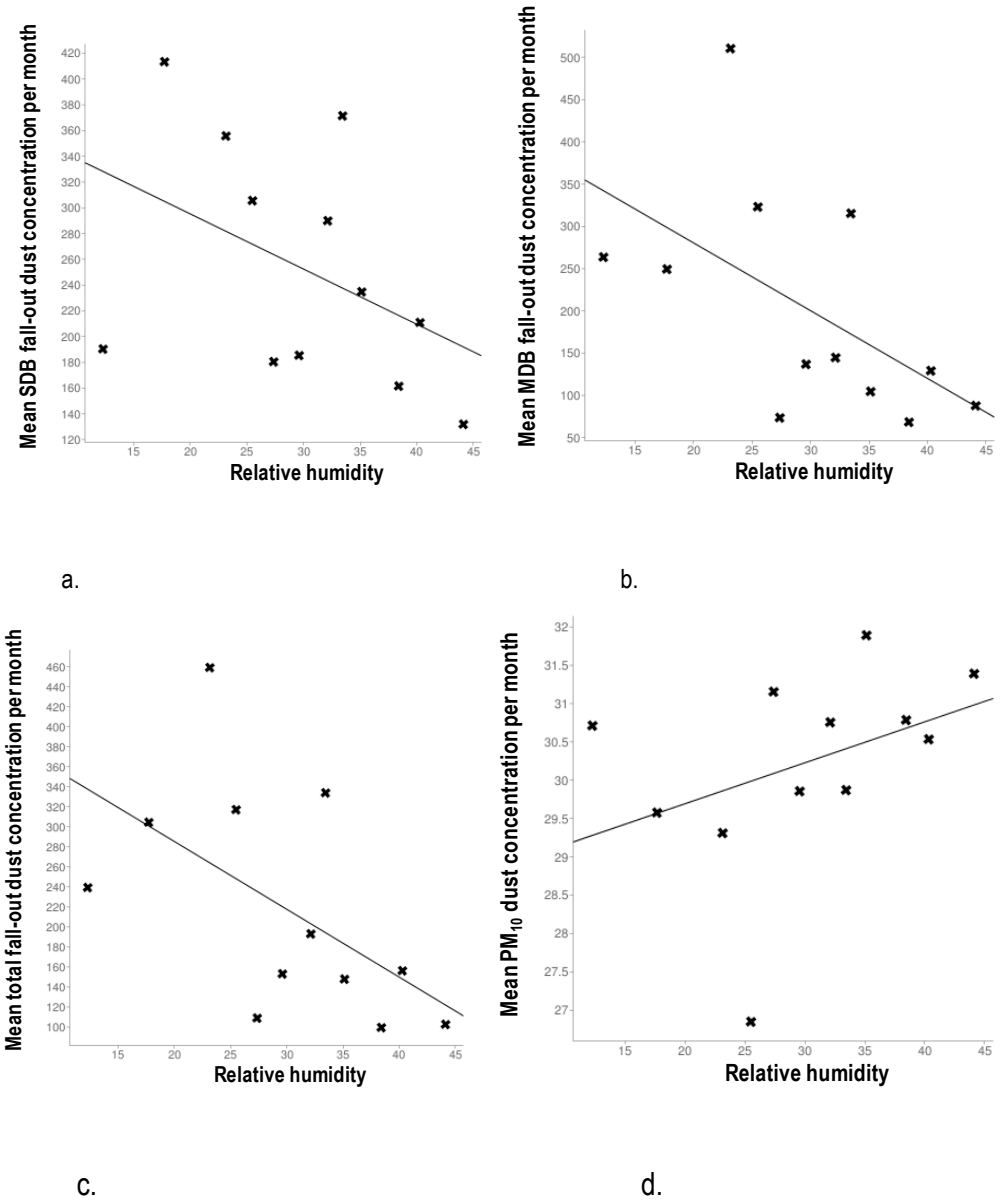


Figure 5.2 Scatter plots and regression lines for relative humidity and dust concentration. a. SDB dust concentration, b. MDB dust concentration, c. Total dust concentration, and d. PM_{10} particle concentration.

5.4 Discussion

The degradation of air quality is major problem in mining areas. Particularly at surface mines, dust in diverse size ranges is generated in large qualities through operations such as drilling, blasting, loading, transport, and unloading (Csavina *et al.* 2012). Dust is emitted directly into the atmosphere from these operations. Transportation through the atmosphere and eventual settlement of dust depends on environmental factors. This study showed that wind speed played a significant role in fall-out dust deposition. The stronger the wind speed, the greater the ability of the wind was to transport fall-out dust away from the place where it was produced, which supports the findings of previous studies (Csavina *et al.* 2012; Patra *et al.* 2016). Similarity to other studies (Giri *et al.* 2008; Krynicka and Drzeniecka-Osiadacz 2013; Afzali *et al.* 2014), wind speed diluted PM_{10} particles by dispersion and hence decreased its concentration in the atmosphere. Relative humidity, on the other hand, played a lesser role when compared to wind speed, probably because of the low precipitation at the time of the study. However, the results did show that relative humidity did prevent fall-out dust deposition and to a lesser extent PM_{10} particle deposition.

Chapter 6

Discussion and Conclusions

6.1 Introduction

The study was conceived since little is known about the composition of dust and the worker dust exposure levels at various stages of the iron ore mining process. Because it is known that dust may be hazardous to human health, it is vital to obtain an understanding of the dust levels and dust composition at this mine. Therefore, the study was conducted to determine the concentrations of the different types of dust generated at an iron ore mine. Two different processes were used to collect fall-out dust, single dust buckets (SDB) and multi directional dust buckets (MDB). The concentration of the PM_{10} particulate matter was also determined. Dust collected during the study was also analysed for the chemical content thereof. In addition to the above-mentioned certain environmental factors were monitored during the study for possible impact on the dust concentration measured during the study period.

6.2 Discussion and conclusions

The tests revealed that the fall-out dust concentrations of the different directional buckets at the different MDB monitoring points did not reveal significant differences. This could mean that it might not be feasible to monitor fall-out dust with multi directional dust buckets. It is financially more viable to utilise single dust buckets.

The data revealed that the concentrations of fall-out dust of the different categories varied substantially over the year. The graph shows that during the months of August and September the dust load was high for both SDB and MDB concentrations. It further indicates that the dust loads of

SDBs and MDBs were substantially less during the first few months of the year when compared to August and September. The fluctuation of the PM_{10} concentrations was relatively low.

The study showed that the dust generated during mining operations were at a level that pose a potential risk, not only to human health, but also to the environment (Csavina *et al.* 2012). The results also indicated that the workers at this particular mine may be exposed to high concentrations of fall-out dust, as well as smaller particulate dust matter, such as PM_{10} particulate dust matter and smaller.

Most of the chemicals found in the fall-out dust after analyses were within both OEL and EEL. However, the results did show that the three elements barium, copper and iron demonstrated noticeably higher concentrations than the other elements. The concentrations of copper and iron exceeded both the OEL and EEL at all the dust monitoring points. Barium, on the other hand, exceeded the EEL at all the dust monitoring points, while the concentrations at only two of the dust monitoring points exceeded the OEL.

The results of the chemical analyses of the collected dust demonstrated an iron and copper content that exceeded both the OEL and EEL. Literature also indicated that, depending on the type of mine, the chemical content might be elevated (Meza-Figueroa *et al.* 2009; Brotons *et al.* 2010; Csavina *et al.* 2012). The health effects of copper-bearing dust exposure range from pnuemoconiosis to skin irritation (Nemery 1990, Agency for Toxic Substances and Disease Registry 2004). Several other studies on dust exposure and the resultant health effects indicated a wide range of illnesses and symptoms inlcuding lung cancer to decreased brain function in people with Parkinson's and Alzheimer's disease (Berico *et al.* 1997; Soukup *et al.* 2000; Ghio and Devlin 2001; WHO 2003, Boyd *et al.* 1970; Kinlen and Willows 1988; Chau *et al.* 1993; Wild *et al.* 2009).

Dust particle size affects dust deposition efficiency in the human respiratory system upon inhalation. Coarse particles, such as fall-out dust is deposited in the upper respiratory system, swallowed, goes through the digestive system and may be absorbed, depending on their bioavailability. In contrast, fine particles, such as PM_{10} and smaller particulate dust matter may be respired deep into the lungs where they can be transported directly to the blood stream (Krombach *et al.* 1997; Park and Wexler 2008; Valiulis *et al.* 2008).

Mining is first and foremost a source of mineral commodity that all countries find essential for maintaining and improving people's standard of living. As mining activities increase, the effects on climate change and the impact on the air quality will negatively influence the health status of miners and the surrounding communities (Csavina *et al.* 2012). Environmental factors, such as wind speed, will influence the deposition of smaller particles such as PM_{10} both in concentration and distances that the particles may travel through the air from the dust source (Csavina *et al.* 2012; Patra *et al.* 2016; Giri *et al.* 2008; Krynicka and Drzeniecka-Osiadacz 2013; Afzali *et al.* 2014).

It can be concluded from this study that more research should be conducted over a longer period of time to determine if there is an actual difference in the multi-directional fall-out dust bucket monitoring system. Research should be conducted specifically to determine if there is a need to use this system or if the single fall-out dust bucket system is sufficient to determine fall-out dust monitoring, since the current study show the multi-directional bucket system to be redundant.

It is clear from this project that the chemical composition of the collected dust shows the highest concentration in the chemicals that are mined; therefore, the environmental concentrations of these chemicals were measured as the highest during the study period. Special control measures should be implemented to reduce the concentration of these particular chemicals in the environment.

Control measures should be implemented more vigorously during the dry windy months of the year since it was apparent from the study that the dust concentrations increase significantly during this period of the year. These control measures should be sufficient to protect both humans and the environment.

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Appendix A

Microbalance operating procedure

The Citizen microbalance is an electronic device that is used for gravimetric mass determination of particulate matter collected on a filter paper. The filter is placed on a weighing pan contained in a draught proof enclosure, stationed on a shock and vibration free level surface. The weighing pan is coupled to extremely sensitive mechanical compounds, which in turn are connected to electronic circuits that display the mass of the object under test on a digital display screen.

Before measurements are done check the following aspects:

- Calibration status of instrument.
- Connection to mains.
- Inspect instrument for visible damage and cleanliness.
- Placement of scale on antistatic mat.
- Zero the scale.

Method of operation

- Guard against fluctuations in temperature.
- The microbalance should not be exposed to direct sunlight.

- If the microbalance was switched off for any reason, a warm-up period of 30 minutes should be allowed before calibration and weighing could commence.
- Before use, ensure that the instrument is level by inspecting the build-in spirit level.
- A centring disc should be used in conjunction with the weighing pan.
- The stability detector should be set to its most sensitive position. The integration time should be set to the longest period.
- Internal calibrate the instrument according to the manufacturer`s instructions.

Microbalance requirements and recommendations

- Must be located in a controlled environment, as described below.
- Should be located on a clean, vibration-free surface.
- Should be located in an environment free of air pulses or turbulence which might prolong or disrupt efforts to achieve stable weights.
- Maintained and operated strictly to manufacturer`s instructions.

Controlled environment requirements

- Mean temperature: 20-23°C
- Temperature control: ±2°C over 24 hours
- Mean humidity: 30-40% RH
- Humidity control: ±5% RH over 24 hours

Filter conditioning and weighing requirements

- Must be conditioned in the controlled environment for a minimum of 8 hours prior to weighing.
- Must be conditioned in the same controlled environment in which the balance is kept.
- Both pre- and post–sampling weighing should be carried out on the same balance, preferably by the same analyst.
- An effective technique must be utilized to neutralize static charges on the filter.
- The pre-sampling weighing must be carried out within 30 days of the sampling period.
- The post-sampling weighing must be carried out within 10 days after the end of the sampling period.
- Weighing room blanks must be kept as quality checks.

Balance room recommendations

- The balance room will its own independent temperature and humidity control systems, and therefore it`s own circulation system. These systems may consist of an air conditioner.
- Continuous measurements of temperature and relative humidity should be visible to the operator and retained.
- The balance room should have sufficient ventilation to properly condition the filters. However, air flow rates in the area of the microbalance should be very low.
- There will be no entrance to and/or exit from the weighing room while weighing is in progress.

- The balance room should be cleaned only by the operator and not by the facilities janitorial staff. The use of cleaning solvents or any other chemicals on the balance and table should be discouraged.

- In order to minimize vibration the balance is located on a heavy table, like marble.

Note

Should the balance need re-calibration, it is no reason to invalidate the results. It is the relative differences in filter masses which is important and not their absolute values.

Appendix B

Step by step description of the method used to obtain the dust data

Bucket preparation

- Clean buckets well and ensure that no particulate or dust remains in buckets and rinse with distilled water and discarding the rinse water.

- Partially fill bucket with distilled water, allowing for the expected rate of evaporation appropriate to the expected rate of sampling (Table B1) These are rough figures and conditions in the sampling area will dictate exact water requirements.

Table B1. Amount of water required for different climatic conditions.

Weather conditions	Week 1	Week 2	Week 3	Week 4
Hot dry warm periods	2.5 litres	3.5 litres	4.0 litres	4.0 litres and check after 3 weeks
Hot wet warm periods	2.0 litres	2.5 litres	3.0 litres	3.5 litres and check after 3 weeks
Cool dry cold periods	2.0 litres	2.5 litres	2.5 litres	3.5 litres
Cold dry periods	2.0 litres	2.5 litres	2.5 litres	3.0 litres
Wet cold periods	2.0 litres	2.0 litres	2.5 litres	3.0 litres + check after 3 weeks

- It is not critical to measure the water accurately and the above approximations are good enough. It should be noted that with any longer period of measurements

the water should be topped up to prevent total loss of water. This will result in some loss of dust or failure to catch dust adequately during the period when the bucket is dry.

- Add an amount of 5ml to 10ml of copper sulphate to each bucket as an algaecide, depending on how full the buckets will be kept. It is not always necessary to dose top up water with copper sulphate.

- Seal the buckets with the lids and adding labels to the bucket lids.

- Transport the buckets to site.

Bucket collection procedure

- The bucket support cradle must be dropped by unlocking and removing the retaining pin before sliding the support assembly down the pole. Care must be taken with the directional unit not to twist cradle to confuse directionality of buckets.
- One bucket at a time must be removed and replaced with a prepared bucket, using the labelled lid to seal the removed bucket and take care to label the sample buckets correctly.
- Lift the support assembly back into position and lock after retaining pin been replaced.
- Any notes should be made in the field book before leaving to the next unit.
- Check the directional unit`s operation by spinning the selector to ensure free movement.

Filtering procedure

- The clean Buchner funnel assemblies should be fitted with the pre-weighed and marked filter paper, making sure that the filter paper is located to prevent by-pass leakage around the filter.

- The contents of one bucket must be loaded into each funnel after +1mm discard solid are strained out (a small tea strainer work well) and the vacuum pump started.
- Filter number must be entered against the designation of the collected bucket on the assessment form.
- On completion of the filtering process, remove the filters from underneath the Buchner funnel, place it in the petri dishes, partially covering the filters, and allow these to desiccate on a low wattage light box or under a 60 watt lamp about 600mm above the filters.
- The filter and solids must be weighed once the filters have been desiccated. The stage at which full desiccation has been achieved is defined under “Weighing procedure”.
- The filter mass must be noted on the assessment form.
- 100ml of the filtrate solution should be retained if the soluble content of the captured samples is also to be assessed and weighed. The total remaining water must be measured and the quantity added to the assessment sheet to determine the amount of dissolved solid.
- The above filtrate solution should be boiled off over a low Bunsen or heat source (hot plate) to accelerate the boiling off. The initial operation can be undertaken in a microwave oven and the beaker transferred to a hot plate for the final desiccation.
- The filtrate solid form the beaker must be collected and weighed, entering the mass on the assessment form as soluble solids.

Weighing procedure for filter preparation

- Stabilise filters in the laboratory or weighing room for 8 hours or keep stock in an unsealed partly ventilated container so that it are continuously stable for the laboratory conditions.

- Filter papers are individually marked using a ballpoint pen. Ensure that the ink has dried before proceeding with any weighing operations.
- Each filter must be placed in its own petri dish and the petri dishes should also be marked with the filter number and bucket number.

Weighing procedure for filter and filtrate

- Initial desiccation in a dust free environment for a minimum of 2 hours must be allowed or until all sample moisture evaporation has stopped.
- Desiccated filters are placed on the balance and permitted to remain on the pan for about 60 seconds. If there is any indication of a continuous fall in mass, it means that the filter/ filtrate is not completely desiccated and the sample must be removed for further drying.

Calculations

- The cross-sectional area of the buckets is a standard constant in all of the calculations representing the over which the dust collection has been made, 0,02545m².
- The actual mass collected is derived by subtraction of the mass of the filter (mass 1) from the combined mass of the filter and filtrate (mass 2). Mass1 – mass2 = collected mass of dust samples.
- All units should be expressed in milligrams and the value of milligram/square metre/ day derived from the formula:

$$\text{Fall-out rate (mg/m}^2\text{/day)} = \frac{\text{collected mass x 1}}{\text{0.02545 x days}}$$