UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

COMPARISON OF METHODS FOR MEASUREMENT OF DUST DEPOSITION IN SOUTH AFRICAN MINING SECTORS

by

Maphuti Georgina Kwata

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTERS OF SCIENCE IN APPLIED SCIENCES: ENVIRONMENTAL TECHNOLOGY

In the Department of Chemical Engineering
Faculty of Engineering, Built Environment and Information Technology
University of Pretoria

Comparison of methods for measurement of dust deposition in South African mining sectors

Author: Maphuti Georgina Kwata
Supervisor: Dr. Gerrit Kornelius
Co-supervisor: Dr. Bisrat Yibas
Degree name: Master of Science: Applied Science in Environmental Technology

Synopsis

Dust particles in the atmosphere are a key cause of nuisance, health and other environmental problems. The mining sector is a major source of airborne particulate matter caused by operations like terrain clearing, drilling, blasting, tipping and loading and the passage of vehicles on unpaved roads. The nuisance effect of airborne dust can be measured by using dust buckets and/or directional dust deposition gauges. Dust buckets are used to determine vertical dust deposition rates and directional dust deposition gauges are used to determine the direction of the sources.

Traditionally the measurement of the vertical flux of dust, or dust deposition has been used as to indicate the nuisance caused by coarse suspended particulate matter. Several countries have produced standards for permissible dust deposition rates. Although alternative deposition measurement methods have been proposed, ASTM D1739 has remained the method most often used in the South African mining and industrial sectors to measure dust deposition. In addition, a number of non-standard directional dust deposition gauges have been used.

SANS 1929:2005 (South African National Standards, 2005) prescribes the use of ASTM D1739:98 for measuring dust deposition. However, for historical reasons the previous version, ASTM D1739:70 (re-approved as ASTM D1739:82) is still widely used and in the recently promulgated South African Dust Management regulations the use of this version is prescribed. In order to determine the difference in the results obtained by the two versions, ASTM D1739:82 and ASTM D1739:98 were used to measure dust deposition levels arising from a coal mining operation in the Mpumalanga Province and a gold mining operation in North-West Province.

In order to determine whether a correlation exists between vertical dust flux (dust deposition) and horizontal dust flux, standard directional horizontal dust flux gauges according to BS 1747 part 5 were also set up at both sites. The measurement of dust deposition using three dust deposition gauges (i.e. ASTM D1739:82, ASTM D1739:98 and BS 1747 part 5, directional dust deposition gauges) was undertaken monthly over a period of fourteen (14) months at the two sites.

The findings of the study indicate that the dust deposition rates for an opencast coal mine are generally higher than the dust deposition rates for an underground gold mine. ASTM D1739:98 was shown to be a more efficient dust deposition collection method than ASTM D1739:82, with the ratio between the mean values slightly more than 2. The addition of water to the dust bucket does not make a statistically significant difference to retention of dust in the bucket. There is a weak correlation between results for the vertical dust gauges and horizontal dust flux.

It is recommended that the South African mining sector continue dust deposition monitoring and reporting using the more recent version of ASTM D1739, as high deposition levels may indicate a potential health impact from PM_{10} thoracic dust.

Keywords: dust deposition, directional dust deposition gauge, horizontal dust flux, American Society for Testing and Materials (ASTM).

Table of Contents

Declaration by the Student

1. I understand what plagiarism entails and am aware of the University of Pretoria policy in this regard.
2. I declare that this thesis is my own original work. Where someone else's work has been used (either from printed source, internet or any other source), this has been properly acknowledged and referenced according to the departmental requirements.
3. I have not used work previously produced by another student or any other person to hand in as my own.
4. I have not allowed, and will not allow, anyone to copy my work with the intention of passing his or her own work.

Signed on the ………………………………day of February 2014.

____

Maphuti Georgina Kwata

Acknowledgements

The author wishes to thank the following people for their help during the investigation. Without their help, it would not have been possible:

The Council for Geosciences for financial support for tuition and registration fees and the National Association for Clean Air for financial support and for funding fieldwork.

Dr. Gerrit Kornelius, Supervisor: University of Pretoria Department of Chemical Engineering for proposing this research study.

Dr. Bisrat Yibas, Co-supervisor: Council for Geosciences-Environmental Geosciences Unit.

Dr. Nina Strydom and Ms. Jaqui Sommerville: University of Pretoria Department of Statistics for assistance with the statistical analysis.

Ms. Mpumi Msezane, Mentor, Parsons Brinckerhoff Africa, Manager: Social and Environmental Section.

Ms. Danel Van Tonder, Co-mentor and supervisor: Council for Geosciences-Environmental Geosciences Unit.

Mr. Danny Ramsuchit and Mr. Philip Ramphisa and the Gold Fields management.

Ms. Marie Engels, Mrs. Janel Hayes, Ms. Kgaogelo Moshokwa and Mr. Jerome Ncazi of AngloCoal Safety, Health and Environment section for their invaluable help and ensuring that the investigation took place quickly and efficiently.

List of Abbreviations

ASTM	American Society for Testing and Material
BS 1747 part 5	British Standards 1747 part 5
BS 1747 part 1	British Standards 1747 part 1
BSI	British Standards Institution
BSNE	Big Spring Number Eight Sampler
DEA	Department of Environmental Affairs
GLM	General Linear Models (a statistical procedure)
GDP	Gross Domestic Product
MDCO	Marble Dust Collector Sampler
MWAC	Modified Wilson and Cooke Sampler
PM_{10}	Dust with an average aerodynamic diameter (d_{50}) less than 10 µm
$PM_{2.5}$	Dust with an average aerodynamic diameter (d_{50}) less than 2.5 µm
PVC	Polyvinyl Chloride.
SANS	South African National Standards
SAWS station	South African Weather Services station
SUSTRA	Suspended Sediment Trap Sampler
US-EPA	United States – Environmental Protection Agency
UV	Ultra Violet
WDFG	Wedge Dust Flux Gauge
WHO	World Health Organization

Definitions

Deposited matter: any dust that falls out of suspension in the atmosphere (International Aluminium Institute, 2012).

Dust: airborne particulate matter with a diameter smaller than 100 micrometers (Implex Limited, 2012).

Dustfall and **dust deposition** are used interchangeably.

General linear models: is "a flexible generalization of ordinary linear regression that allows for response variables that have other than a normal distribution" (Swaminathan, Lu, Williams, Lu and Jablonski, 2013) and also allows the "magnitude of the variance of each measurement to be a function of its predicted value" (Hamilton, 1994; Tsay, 2005).

Light commercial areas: "any area classified for light commercial use as per local town planning scheme" (Implex Limited, 2012).

Meteorology: "the earth science dealing with phenomena of the atmosphere (especially weather)" (Free Dictionary, 2005).

Residential area: "any area classified for residential use per the local town planning scheme'' (Implex Limited, 2012).

List of Tables

List of Figures

CHAPTER ONE: INTRODUCTION

1. Introduction

In the mining sector, dust is mainly generated through transport, handling, processing of minerals and windblown dust from tailings dams. Processing includes the steps shown in figure 1.1 below, although not all of these steps occur at all mines. Dust causes health and environmental effects, such as air, soil and water contamination. In addition, mine dust increases the loss of raw material and causes surface soiling on mining machinery which increases maintenance costs, thereby creating adverse economic effects (Jia, 2008).

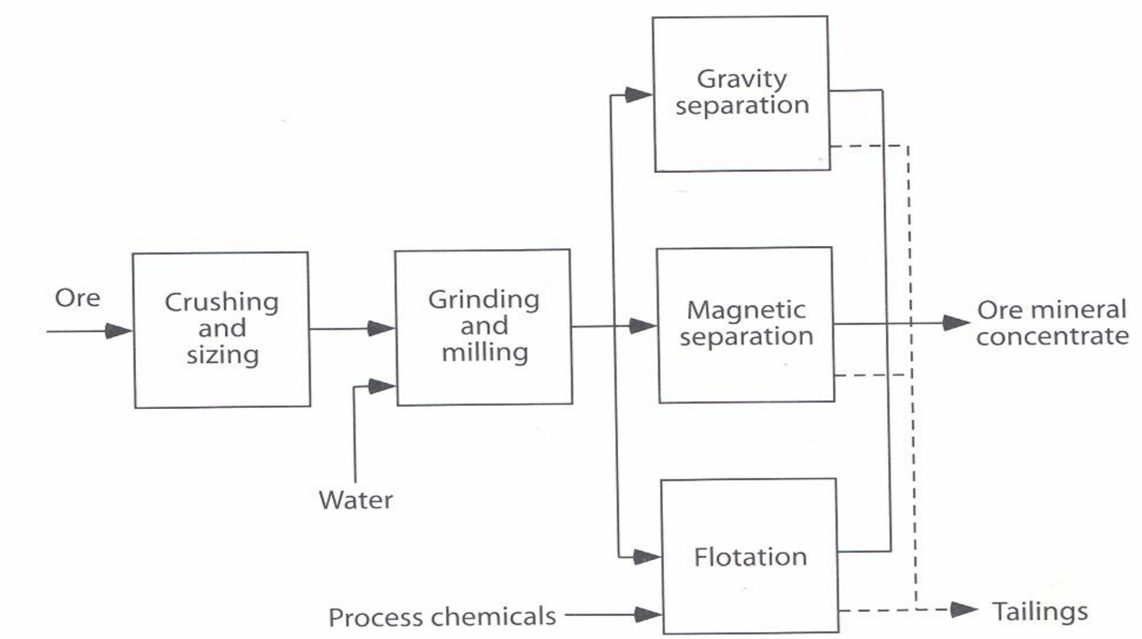


Figure 1.1: A simplified flow chart of mineral processing (Lottermoser, 2003).

1.1 Air quality impact of mining

South Africa has a vast array of mineral resources which include gold, coal, platinum, diamond and base metals. Mining is a key contributor to South Africa's gross domestic product (GDP). For example, mining has contributed an average of 20% to the GDP (Statistic Department South Africa, 2007; 2008). However, there are environmental and social impacts associated with mining and these include water and air quality deterioration and land-use changes. "One of the mining-related air pollutants is dust, which is also caused by a series of activities resulting from industry, household and manufacturing functions. In minerals processing, dust is emitted from:

- Wind-blown dust from mine tailings storage facilities.
- The effect of the break-down of ore through crushing, grinding, abrasion and force, etc.
- Mine activities such as loading ore for transport, dumping and moving it from on area to another which liberates dust already created by other activities.
- Through recirculation of dust already created by other activities by breezes or the movement of people working on the mine and equipment" (OSHA, 2008).

"The amount of dust emitted by these activities depends on the physical characteristics of the material and the way in which the material is handled. Excess dust emissions can cause both health and industrial problems, such as:

- Risk of dust explosions and fire.
- Damage to equipment.
- Impaired visibility.
- Unpleasant odors.
- Problems in community relations.

Health hazards include:

- Occupational respiratory diseases.
- Irritation of eyes, ears, nose and throat.
- Irritation to skin" (Parker, Schoendorf and Kiely, 1994).

1.2 Definitions of dust

"The health impacts associated with dust produced in mining operations have been known for centuries. This has resulted in much time and effort being spent on researching ways in which dust is produced, how it behaves in the environment, how it is measured and controlled and how it affects human beings physiologically when exposed to it.

Dust is defined as a finely-divided solid matter, depending on its particle size, concentration and composition. There are several parameters or combination of parameters, which have been used to describe or define dust and the extent to which it is present in the atmosphere. The most important of these are:

1) Number of particles per unit volume;
2) Size distribution of the particles;
3) Mass of dust per unit volume;
4) Surface area of dust per unit volume;

5) Chemical composition;
6) Mineralogical nature of the particles" (Parker, Schoendorf and Kiely, 1994).

Dust can be classified as total particulate matter, fine particulate matter, nuisance dust, respirable dust and thoracic dust. Below is a brief description of these dust categories:

Total particulate matter refers to all the particles carried by air irrespective of their size or makeup (OSHA, 2008).

Fine particulate matter refers to dust which is smaller than a few µm. It is sometimes used synonymously with $PM_{2.5}$ (Colls, 2002). Fine particulate matter is invisible to the human eye; however where there is a high concentration of fine particles, one may experience it as a 'haze' or 'miasma' in the atmosphere (Doyle, 2012).

Nuisance dusts refer to a high concentration of grainy particulates carried by the air (Coal of Africa Limited, 2014). This may dirty clothing and buildings and has the potential to make vision difficult (Maeda, Moroka, Tsunjino, Satoh, Zang, Mizoguchi and Hatateyama, 2001). *Settleable particulate matter* is often used as a synonym for nuisance dust.

Respirable dust refers to those tiny dust particles that enter the nasal passages and upper respiratory system and penetrate the lungs. In most cases the body's filtering mechanisms, such as the cilia and mucous membranes, are unable to deal with respirable dust and it thus remains (OSHA, 2008).

Thoracic dust comprise those particles of dust with an average aerodynamic diameter of about 10 µm. Thoracic dust is also known as inhalable dust. According to the EPA inhalable dust is the size fraction of dust which enters the body and becomes entrapped in the nose, throat and upper respiratory tract (Hinds, 1982; Parker *et al,* 1994).

Settleable particulate material refers to any material composed of particles small enough to "pass through a 1 mm screen and large enough to settle" by virtue of their weigh into the container from the ambient air (ASTM International, 2010).

1.3 Health and nuisance effects due to dust

"Health effects due to dust exposure are primarily respiratory because it is in the lung that dust interacts with the body. Health effects such as affecting of the lungs, eyes disturbance, nose, mouth and throat, asthma attacks, respiratory symptoms such as coughing and wheezing etc.'' *(*Colls, 2002).

"With the increase of mining on a large scale workers are now exposed to dust in the mining environment" (Combes and Warren, 2005). Exposure to dust for a sustained period can cause recurrent respiratory and lung problems. Respiratory problems like asthma and allergic reactions may be exacerbated. Dust also causes coughing, wheezing and runny noses (Schwela, 1998). Factors which shape the effects of dust on man's health include the size, composition and concentration of the dust particles (Lodge, 1988). Dust has the potential to cause other manifestations of ill health because dust may also contain material that is biologically active. An examples is mineral dusts contain quantities of quartz. This kind of dust can lead to silicosis which is a lung disease if this kind of dust is present in high concentration in the environment (New Zealand MfE, 2000, 2002).

Nuisance effects are "those environmental effects of dust that are or not health-related. The so-called nuisance effects are brought about by any sized particle of dust. However, it is usually related to those of larger than 20 microns" (Maeda *et al*, 2001).

1.3.1 Gold mining

Gold mining in South Africa was initially concentrated in the Witwatersrand Basin where gold was discovered in 1888 but other areas of gold deposits were discovered previously and thereafter and gold mining occurs in the other parts of South Africa, such as Mpumalanga and the Free State. By a far margin the Witwatersrand Basin is a source of most gold (98%) produced in South Africa and this represented a third (30%) of global gold production in 2003 (White, 2003). The northern and western margins of Witwatersrand Basin contain a larger amount of gold deposits (White, 2003).

Dust pollutants released from the various activities in a gold mine can be hazardous to the health of humans. They can also adversely affect the development and survival of plants and crop yields (Goldfields, 2007; 2008).

Dust from mine tailings is probably the most hazardous to the general population by virtue of the quantities released into the environment. Dust from tailings dams can pose serious adverse impacts on humans and their welfare. There are also unsealed and unpaved roads which contribute to the dust generation activities (Goldfields, 2007; 2008). Driefontein mine, where experimental work was carried out during this study, is located in the Witwatersrand Basin.

1.3.2 Coal mining

Coal mining occurs in five South African provinces, namely Mpumalanga, Gauteng, Kwa-Zulu Natal, Limpopo and Free State. A high concentration of coal mines occurs in the Highveld region of the western Mpumalanga. This area is under threat from the effect of air pollution and a significant contribution is made by coal mining among other pollution sources.

The adverse effects of coal are experienced by humankind in various ways: through direct combustion, mining activities and coal fires for domestic use. These represent ways in which the constituents of coal penetrate the surrounding environment both naturally and anthropogenically (American Geological Institute, 1998).

Because of the health impacts associated with dust, it is important to measure dust deposition in order to manage dust impacts. Kleinkopje colliery mine, where experimental work was carried out during this study, is located in the eMalahleni vicinity.

1.4 Measurements methods used for dust deposition in South Africa

The focus of this study is on dust deposition. Therefore only dust deposition apparatus is described in this section.

1.4.1 ASTM D1739

American Society for Testing and Material (ASTM) method D1739 deals with measuring vertical dust deposition or vertical flux. ASTM D1739 measures only nuisance dust (ASTM International 1998, 2010). It consists of a dust bucket, stand and bird guard and in later versions, a wind shield. See figure 1.2.

The previous versions of ASTM D1739 (ASTM D1739:70, ASTM D1739:82) do not prescribe the wind shield, but continue to be used in South Africa in many instances. The addition of water into the bucket at the commencement of the sampling period is included in this version (not referred to in later versions) to improve retention of collected dust. The addition of a wind shield in the most recent version (ASTM D1739:98) is intended to increase the laminar flow across the top of the collecting container, thus better simulating ground level conditions. However, the numerical dust deposition values originally proposed by the Department of Environmental Affairs (Zunckel, Naiker and Raghunandan, 2010) and carried over into South African National Standard SANS 1929:2005 are presumed to be based on the ASTM D1739:70 version and remained unchanged when the ASTM D1739:98 version was introduced into the SANS standard.

a b

Figure 1.2: a) ASTM D1739:82 without wind shield but with a bird ring; b) ASTM D1739:98 with wind shield.

The advantage of the ASTM D1739 method is that it is simple and economical and it can thus be deployed at multiple sites to obtain a more detailed spatial distribution of dust deposition rates. The gauge is easy to install, does not require electricity in order to function and can be operated by personnel with little training.

The disadvantages of the ASTM D1739 method are that it measures only nuisance dust deposition and thus is not directly related to any health effect. Since only one measurement per month per site can be obtained by the use of this method, it is not sensitive to individual dust episodes. Another major drawback of using this apparatus is that it can be easily stolen and vandalized.

1.4.2 Directional dust deposition gauge

A directional dust deposition gauge measures dust deposition and provides the direction of the source of dust. The gauge is relatively inexpensive, thus permitting more measurements by installing more gauges, e.g. along a line route. “The contaminant collection efficiency of the gauge is greater for coarser particles and less for finer particles” (Ralph and Hall, 1989).

The British Standard BS 1747 part 5 directional dust deposition gauge is described in (British Standard Institute, 1972) and shown in figure 1.3 below. The gauge was used by Eskom, the South African national power utility in the first “insulators pollution survey undertaken in the country from 1974 to 1976” (Mace Technologies, 2008). The survey was designed to measure the pollution severities and correlate this with the performance of the electrical insulators. The gauge has four vertical tubes each with a slot milled on the vertical face and facing the four principal wind directions. Bottles which collect the dust blown into the slots are attached to the bottom of each tube. “The advantage of the gauge is that no electricity supply is required; the gauge is relatively inexpensive and is simple to use. Measurements can be undertaken by local unskilled personnel” (Mace Technologies, 2008).

It should be noted that, having vertical openings, the directional gauge is a horizontal flux gauge, measuring the horizontal flux of particulate passing through the measuring station.

Figure 1.3: Directional dust deposit gauge (British Standards Institute, 1972).

The three dust monitoring methods described above (ASTM D1739:82, ASTM D1739:98, BS 1747 part 5) were used in the present study. To complete the description of nuisance dust measurement apparatus most commonly used in the SA mining sectors, a brief description of the Dustwatch monitoring method, which is often used by the South African mining industry to determine the direction of the dust source, follows in the ensuing section.

1.4.3 Dustwatch

Dustwatch is a type of dust deposition monitoring equipment which relies on the wind to rotate a horizontal plate or lid with a hole located over the top of four vertical buckets, thereby exposing different buckets during periods of different wind direction as shown in figure 1.4. It is used for identification of the direction of dust sources. Although the manufacturers claim that results obtained by the Dustwatch apparatus are directly comparable to those obtained by the ASTM method (Kuhn, 2011), no data are available on the correlation between results obtained by this apparatus and the ASTM D1739 method. Differences may occur due to the partial opening of buckets under some wind directions as well as the impact of the lid on the flow regime over the buckets.

Figure 1.4: Dustwatch.

1.5 Problem statement

In some cases, particularly in the South African mining areas, dust pollution has a large impact on the environment and in the life of human beings. Therefore, it is important to do a proper study on dust monitoring methods used in these areas. It is important (i) to compare two versions of ASTM methods differing in the absence or presence of wind shield; (ii) test for the effect of water in the sampling bucket on dust capture (ii) to compare standard methods for vertical and horizontal dust flux.

Specific objectives of the study are to:

- compare two methods widely used for measurement of vertical dust flux in South Africa at present;
- compare results obtained from vertical dust flux measurement with results obtained by a directional dust deposition gauge, which measures horizontal flux in an attempt to determine the direction of sources of nuisance dust.

The approach of the study is:

- to make use of dust sampling instruments which are capable of quantifying or measuring the nuisance impact of atmospheric dust;

- to compare dust monitoring methods used internationally and locally for measuring nuisance dust.

1.6 Significance of the study

The research may assist the Department of Environmental Affairs (DEA) to implement the dust control regulations and select appropriate dust deposition rates to include in the regulations.

1.7 Limitations of the study

The research findings are limited because the study was conducted on only two sites. Site specific conditions might have affected the dust deposition rates. These have not been addressed in this study.

1.8 Structure of the thesis

The thesis consists of six chapters.
Chapter One contains a general introduction to the study, definitions of dust, health and nuisance effects, types of methods used to measure dust deposition in South Africa, problem statement, objectives, specific objectives, the approach of the study, significance and limitations of the study.
Chapter Two summarizes the literature review on dust and dust deposition, dust flux monitoring instruments, vertical deposition gauge and horizontal dust flux and their types, comparative studies, laboratory studies, development of standards, definition of standards and the South African deposition guidelines and standards.
Chapter Three discusses the methodology adopted for the study. The methodology consists of planning of the study, selection of the site and site description, sampling, data collection, procedures and analysis, data analysis, dust monitoring equipment and interpretation tools/methods.
Chapter Four presents the results of the study by comparing raw data for seasonal dust rates from vertical deposition gauge and horizontal dust flux by comparing the results from vertical deposition gauges within mining sectors separately and then overall, for three vertical deposition gauges and total sum of horizontal dust flux.
Chapter Five present the conclusions and recommendations of the study.
Chapter Six present list of references which were used in the thesis.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter deals with previous studies on methods used for measurements of dust deposition in industries and residential areas in various countries as well in South Africa. It includes various key definitions, the distinction between various dust deposition measuring instruments, a brief comparison of these methods and the South African dust deposition standards.

2.2 Dust and dust deposition

Dust is defined as "any solid particle with an aerodynamic diameter less than 100 µm" (Barnard, Friend and Visser, 2006). Dust deposition occurs when dust particles with an aerodynamic diameter greater than approximately 20 µm that have been entrained into the air by a physical process, such as wind, movement of vehicles or stack emissions, are deposited on a solid surface. These particles are generally too heavy to remain in suspension in the air for any period of time and hence deposit on surfaces over a relatively short distance from the source, depends on the combination of various aspects, such as the size of particle, density, temperature (of the air and particle), emission velocity or method, ambient wind speed and humidity. These particles are therefore commonly known as "deposited dust" (Peterson, Karl, Kossin, Kunkel, Rimore, McMahon, Vose and Yin, 2013).

The particulates in this range are generally classified as nuisance dust and can cause physical damage to property and physical irritation to plants, animals and humans. The "dust may have concrete effects on plants", such as obstructing and injury to stomata, "shading, abrasion of leaf surface or cuticle," and cumulative effects, for example, in species already stressed by lack of moisture, dust causes greater stress. Moreover, if dust has harmful chemical constituents as in the case of mining dust, these effects, either directly to vegetation or the ground, will be more injurious than the physical effects (Mineral Industrial Research Organisation, 2014) (figure 2.1). The dust deposited on the soil may cause changes in soil chemistry, which may alter plant chemistry, species and community structure over a long period (Grunhage, Dammneg, Kuster and Jager, 1993). Certain areas are ecologically vulnerable and agricultural resources may be more sensitive to dust than other areas. "Examples of these kind of areas include designated nature conservation areas containing vulnerable species, areas where intensive horticultural is carried out and fruit orchards and farms" (Grünhage, Dämmgen, Kuster and Jäger, 1993).

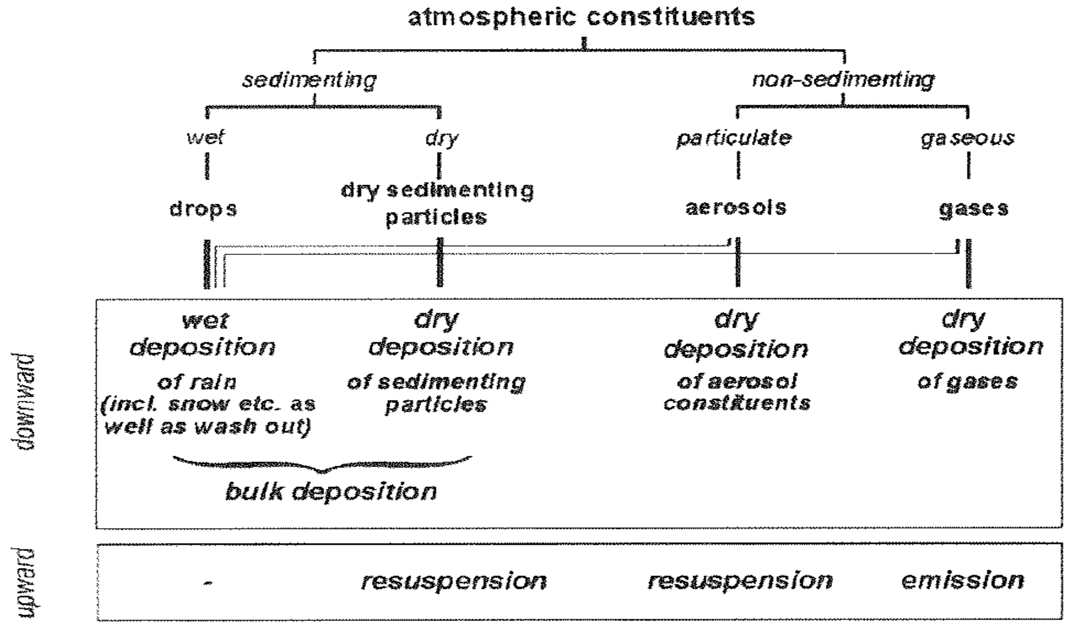


Figure 2.1: Air constituents with respect to their deposition properties (particles size and mass, states) in order to derive flux detection methods (Dämmgen, Erisman, Cape, Grünhage, and Folwer, D 2005)

In-depth studies of the effects of dust deposition on ecology and agriculture are few. The effect of dust is shaped by a range of variables as follows:

- the levels of the concentration of dust particles in the ambient air and associated deposition rates.
- features of the plants and leaf surface, such as surface roughness and wetness, which influence the rate of dust deposition on vegetation.
- "meteorological and local microclimate conditions and degree" of the entry of dust into vegetation.
- the distribution of dust particles of different sizes.
- chemical make-up of dust - going from highly alkaline dusts (such as found in limestone quarries), to inert dusts, and dusts which are highly acidic (such as dusts which arise from coal mining) (Grünhage *et al*, 1993).

2.3 Dust flux monitoring instruments

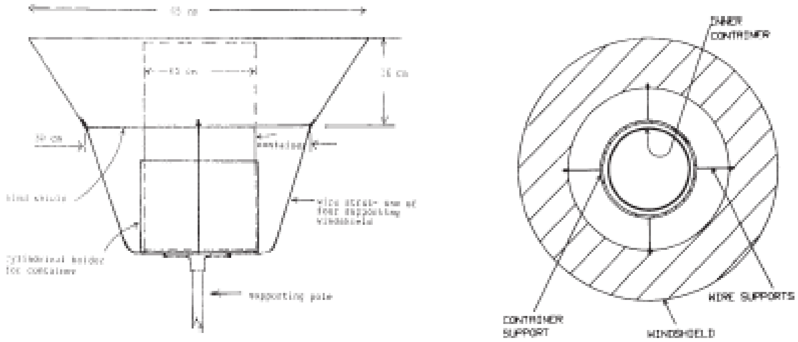
Dust flux monitoring instruments are used to measure dust deposition rates and the direction of the source of deposited material. The dust flux monitoring instruments are also used to determine the average particle concentration in the air passing the flux gauge. There are two types of dust flux monitoring instruments, namely vertical deposit gauges and horizontal dust flux gauges. The vertical deposit gauges are used to measure the dust deposition rate and horizontal dust flux gauges are used to determine the direction of the emitting source.

2.3.1 Vertical deposit gauge

The vertical deposit gauge is a non-directional method for the monitoring of nuisance dust and it makes use of measurement of mass or the soling of surfaces (Mineral Industrial Research Organisation, 2014). The deposit gauges are specially planned to gather material which has been deposited over an afore-determined period of monitoring, usually from 28 to 30 days. The design principle underlying the deposit gauges is that coarse particles suspended in the air will settle either because of gravity (dry deposition) or because of contact with droplets of moisture (wet deposition) (Environmental Agency, 2003). There are a number of standard vertical gauges to measure dust deposition rates. Some of these are: ASTM D1739:82 and ASTM D1739:98 deposit gauges, BS 1747 part 1 deposit gauge, ISO deposit gauge, Frisbee dust deposit gauge, Nilu dust deposit gauge, Marble dust collector sampler (MDCO) and Metdust (Wind sampler).

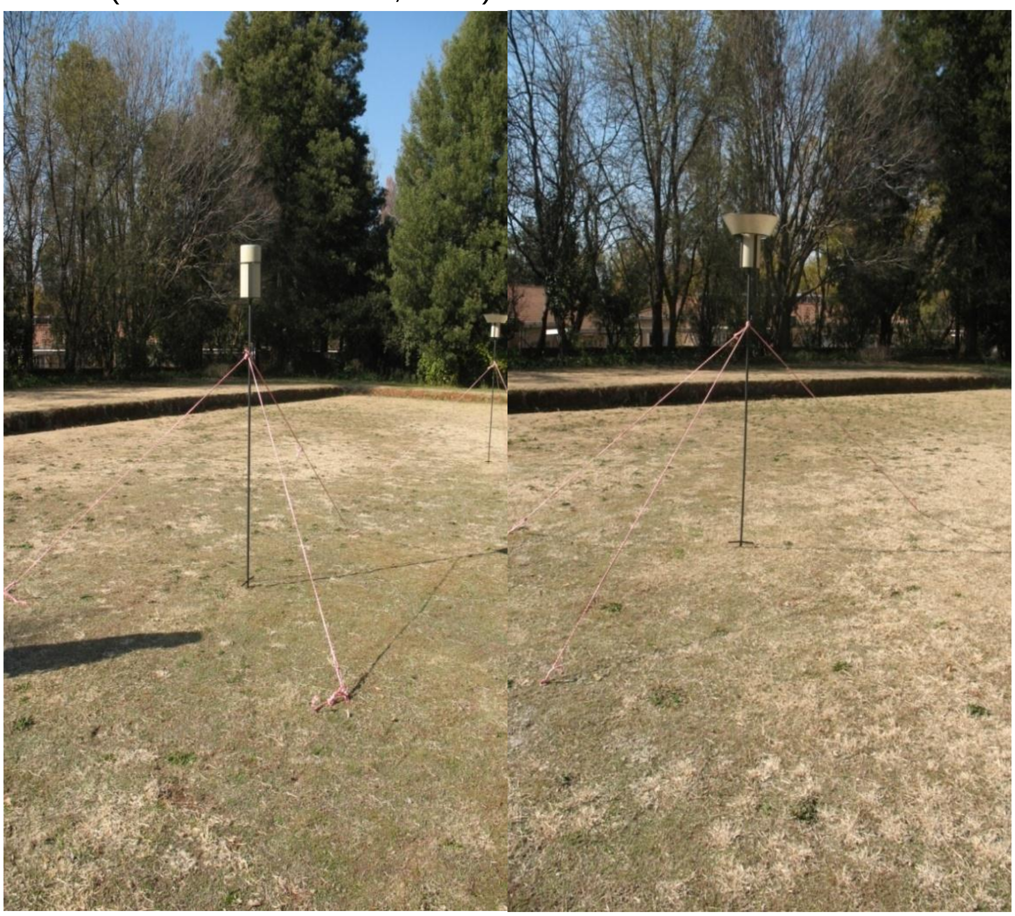
2.3.1.1 ASTM D1739:82 and ASTM D1739:98

ASTM D1739 describes a single bucket monitor which is deployed following the ASTM standard test method for collection and analysis of dust deposition rates (Environment Agency, 2003) (figure 2.2). This method employs a straightforward device comprising a container shaped like a cylinder (in the original method 50% full of deionized water) exposed for 30 days. The cylindrical container (bucket) is supported by a metal frame so that the top edge of the container is 2m above the ground. The dust is deposited into the bucket vertically in two possible ways: dry deposition or wet deposition. The elevation from the bucket rim to higher objects within 20 m should not exceed 30˚ from the horizontal (ASTM International, 1982).



a b

Figure 2.2: a) Wind shield for dust deposit container; b) Plan view of Wind Shield (ASTM International, 2010)**.**



a b

Figure 2.3: a) ASTM D1739:82 without wind shield; b) ASTM D1739:98 with wind shield.

Two versions of the ASTM standard exist, viz. ASTM D1739:82 (see figure 2.3: a) and ASTM D1739:98 (see figure 2.3 b). ASTM D1739:82 has only the bird ring around the top edge of the bucket. In South Africa ASTM D1739:82 has been in use for more than 25 years to monitor dust on mines and industrial sites and it is still in use today. ASTM D1739:82 requires the addition of water into the bucket in an effort to improve dust retention.

ASTM 1739:98 is the later version based on the work of Kohler and Fleck (1969) to compare the performance of vertical flux gauges used internationally (figure 2.4), which introduced a wind shield to improve simulation of near-surface flow conditions at the top edge of the bucket.

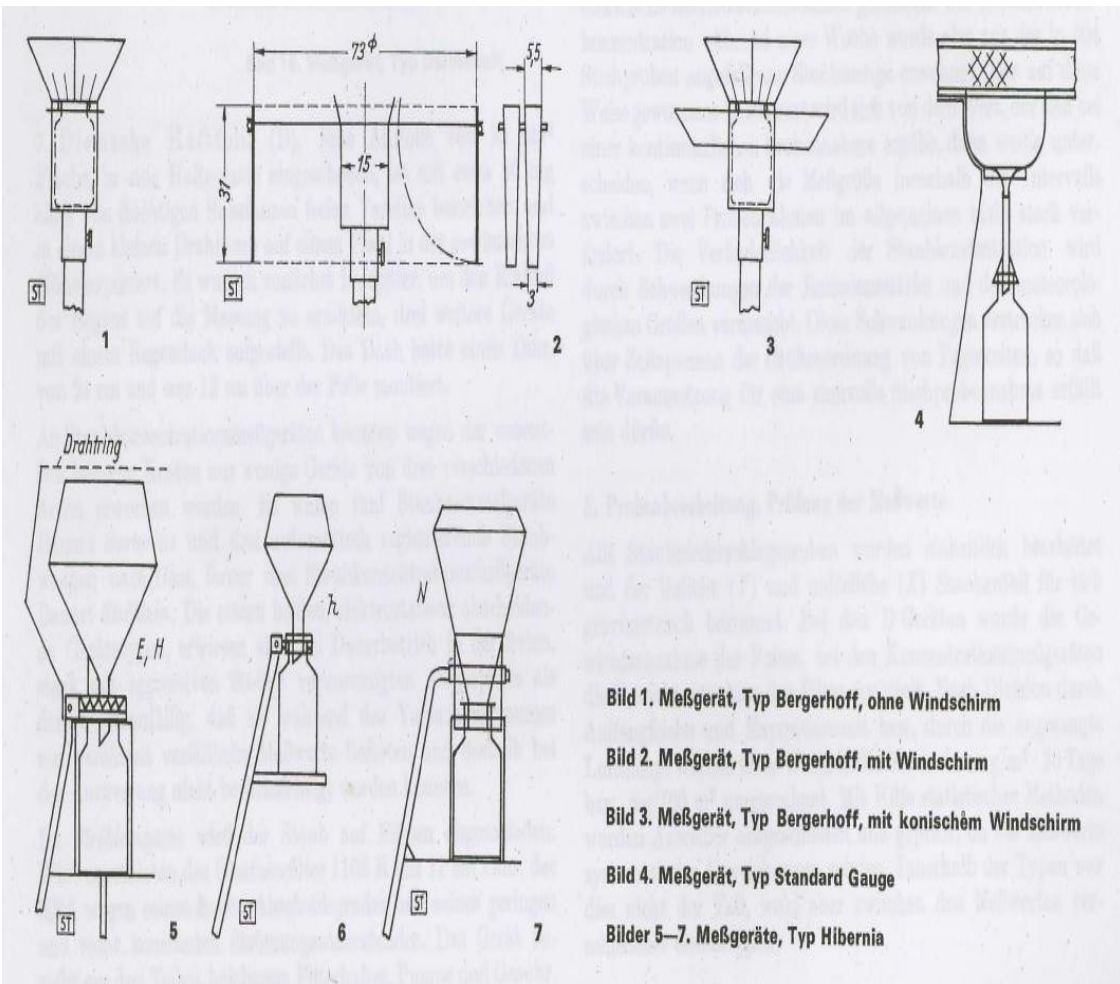
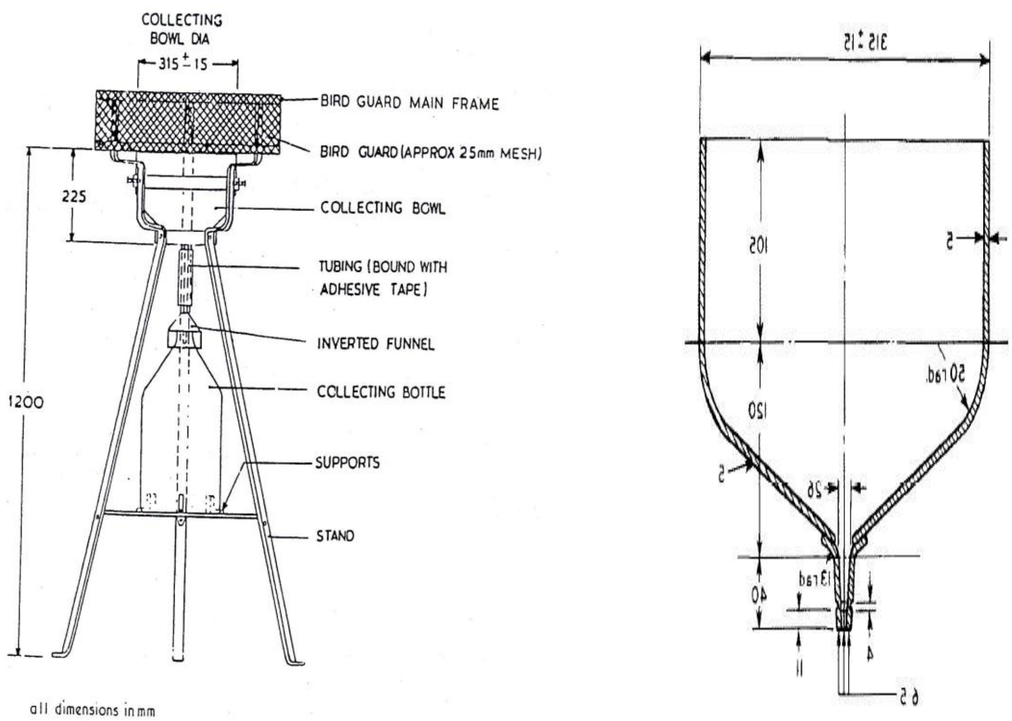


Figure 2.4: 1) Bergerhoff gauge with surface area 61 cm^2, no wind shield ;2) Bergerhoff with wind shield according to Alter; 3) Bergerhoff gauge with conical wind shield according to Kohler and Fleck 4) English standard gauge (BS1747 part 1); 5-7) Hibernia-type gauges with different dimensional ratios (Kohler and Fleck, 1969).

Ralph and Barrett (1989) point out that the 'bird guard' on the 'English gauge' (no 4 in figure 2.4, also figure 2.5 below) is made by a plastic mesh with 60% open area and this may contribute to poor performance.

2.3.1.2 British standard 1747 part 1 deposit gauge

British Standard 1747 part 1 deposition gauge is used to collect dust that falls into the bucket vertically. Dust is collected for a period of one month (30 days) (figure 2.5).



a **b**

Figure 2.5: a) BS 1747 part 1 deposit gauge diagram; b) BS 1747 part 1 deposit gauge (Ralph and Barrett, 1984).

2.3.1.3 ISO deposit gauge (ISO/DIS 4222)

The ISO deposit gauge comprises of an "upward facing contained made of polythene and shaped like a cylinder with the top edge chamfered outward at 45˚. The top of the cylinder is approximately 1.7m above ground level" (Du Droit, 2010*)* (figure 2.6). Dust collection period is 30 days. The deposition rate is expressed as mg/m^2-d. The gauge has limited collection efficiency and collection of dust depends on the wind speed. The ISO large collecting bucket accommodates 400 mm rain (Du Droit, 2010*).*

Figure 2.6: ISO deposit gauge.

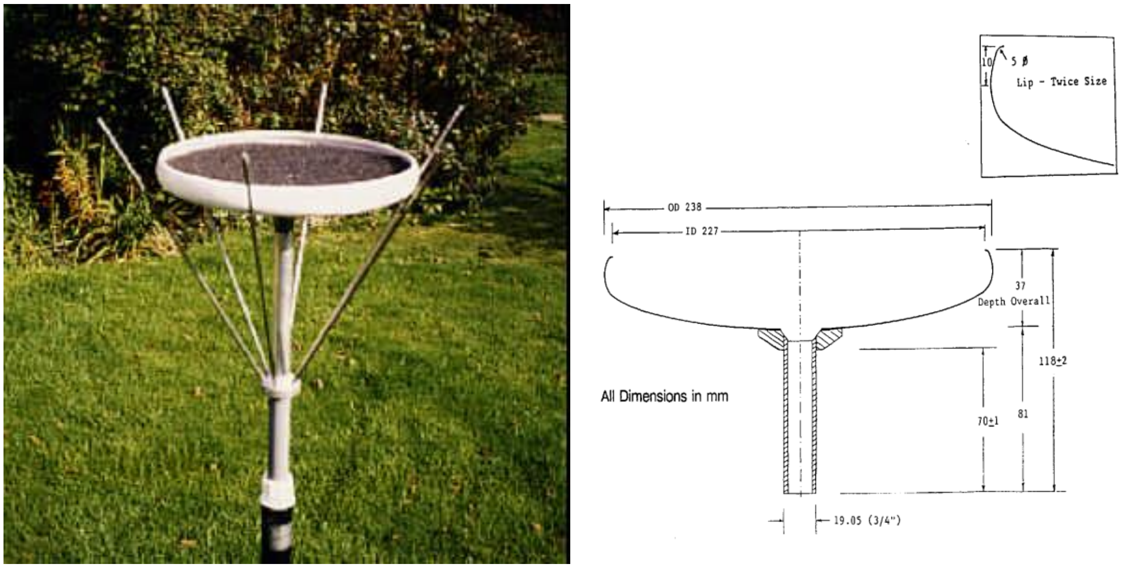
The shortcomings of the ISO deposit gauge are similar to ASTM D1739 gauges: a) they have limited to collection efficiency; b) they are dependent on wind speed; c) they are prone to contamination by leaves and insects. In the case of the ASTM D1739 gauges, the effect of this contamination is mitigated by removal using a 1mm screen during laboratory processing.

2.3.1.4 Frisbee dust deposit gauge

The Frisbee type dust deposit gauges were developed due to the perceived inefficiency of the standard gauges. Frisbee-shaped gauges consist of collecting bowls that are made of anodized, spun aluminum shaped like an inverted frisbee. The frisbee has an aerofoil-shaped collector which improves particle collection efficiency by reducing the acceleration of air flow. "The plastic frisbee is cheap and user friendly for recurring implementation over lengthy time periods due to its flexibility" (Vallack, 1995).

"The frisbee type dust deposit gauge is supported with the opening above the ground level and has an opaque drain pipe that leads from the stem in the center of the collecting bowl down to a rainwater collecting bottle on the ground (figure

2.7). Frisbee-shaped gauges collect samples for a period of one month and the bottle generally has sufficient capacity for rainfall over that period" (Vallack, 1995).



a **b**

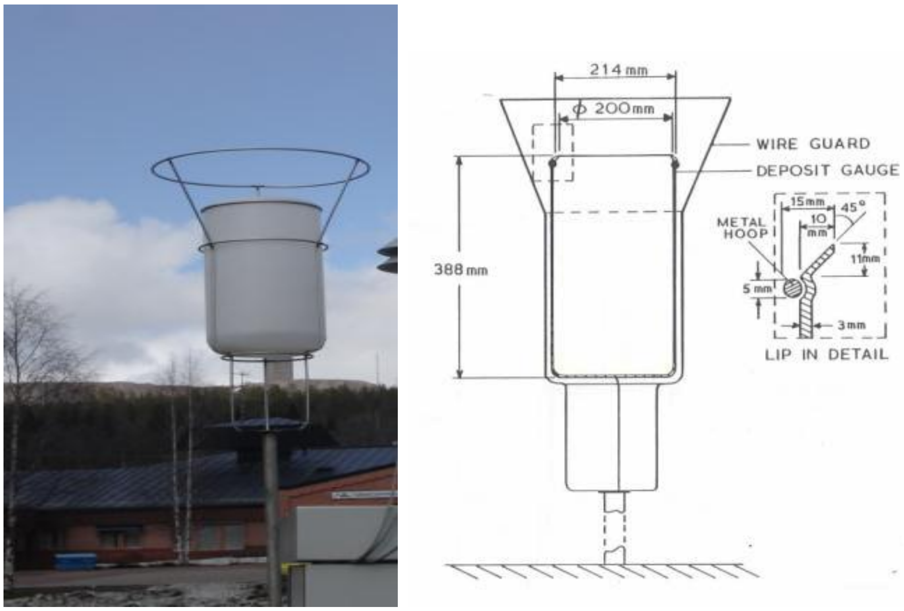
Figure 2.7: a) Frisbee type dust deposit gauge; b) Cross-section through the collecting bowl of the Frisbee type of dust deposit gauge (Pacwill Environmental Limited, 2008).

"The frisbee type dust deposit gauge is placed on a horizontal surface at a fixed location far away from anything that may obstruct, such as constructions, trees and electric wires on which birds might settle"(Pacwill Environmental Limited, 2008). "It is unsuitable to have any sizeable object in an area of five meters of the gauge and, generally, the top of any obstructing object should be spaced more than a 30˚ angle with the horizontal at the point of sampling" (Vallack, 1995).

"The frisbee has two types namely: wet frisbee (coated with liquid paraffin) and dry frisbee (foam insert). The collecting bowl for the dry frisbee gauge is lined with a 10-mm thick, 240-mm diameter, disc of black (10 pores per inch) polyester foam. The frisbee gauge incorporates a bird-strike preventer in the form of a ring of fine (1 mm thick) plastic fishing line (left slightly slack) which is supported by the collecting bowl on six stainless steel struts 5cm above it. The frisbee gauge studies results show that the wet frisbee gauges generally give higher rates of dust deposition than the dry frisbee gauges" (Vallack, 1995).

2.3.1.5 Nilu dust deposit gauge

The Nilu dust deposit gauge was proposed by the Norwegian Institute for Air Research (figure 2.8 a and b) and is available commercially. It has a particulate fallout collector and a precipitation collector with a bird rings (Nilu Norwegian Institute for Air Research, 2010). The stand is adjustable in height to facilitate changing the collectors**.**

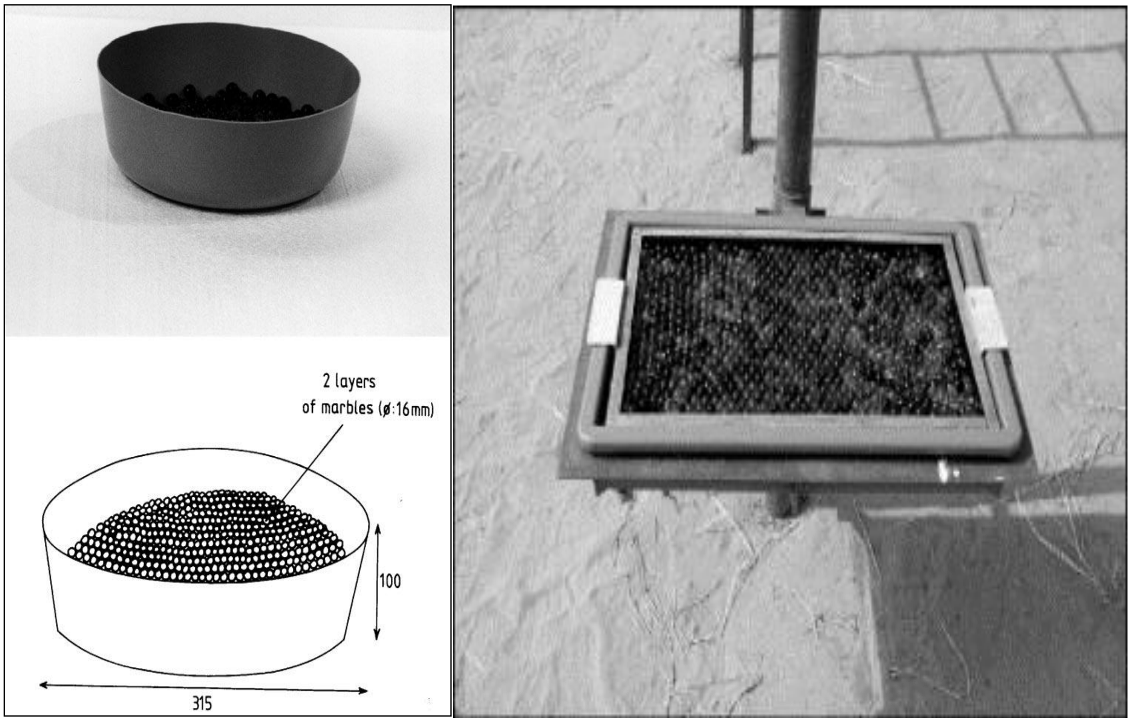


a b

Figure 2.8: a) Nilu dust deposit gauge; b) Dimensions.

2.3.1.6 Marble dust collector sampler

The Marble dust collector sampler (MDCO) is mainly used in desert research and was first described by Ganor in 1975 (Sow, Goossens and Rajot, 2006). The sampler comprises a shallow container with a layer of standard glass marbles which are 1.6 cm in diameter (figure 2.9). It is very cheap, easy to install and hence it is widely used (Goossens and Offer, 2000). These samplers are intended more for geological studies to measure soil accretion or soil transport, rather than monitoring industrial nuisance dust.



a b

Figure 2.9: a) Photograph and construction scheme of the MDCO sampler; b) A rectangular MDCO sampler (Sow *et al*, 2006)

2.3.1.7 Wind sampler (METDUST)

The wind sampler (Metdust) (figure 2.10) was developed to determine the dust deposition rates and measure dust deposition generated by a particular dust source. The Metdust field test is used to assess increased dust deposition rate around a particular dust source (e.g. a coal stockpile) (Fuglsang, 2002). “The traditional bulk sampler measures the rate of dust deposition of high fugitive dust emissions, which usually prove very hard to pinpoint” (Fuglsang, 2002). "The Metdust sampler offers the potential to measure the dust-deposition rate contributed by the source and the background at exactly the same time” (Peterson *et al*, 2013).

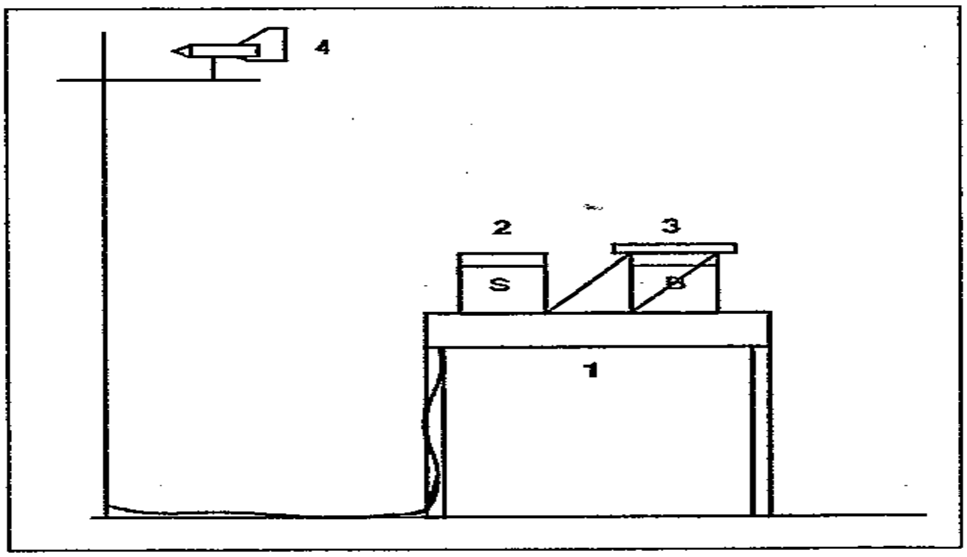


Figure 2.10: Metdust wind dust collector for sampling dust from fugitive source; 1) Console with programmable PLC for control of motor for moving the lid; 2) Collector for sampling of dust from the source (S); 3) Collector for sampling of dust from all other wind directions background; 4) Wind-direction transmitter (Fuglsang, 2002).

"The continuous measurement of wind direction and wind speed take place using a data logger and a relay on the transmitter linked to the data logger to enable a remote control of the positioning of the lid. The data logger is used to measure the wind direction, the wind speed and the lid position in a mean time of five minutes" (Fuglsang, 2002). The fundamental function of the sampling method relates closely to the wet and dry-only sampling technique which is generally used to quantify wet and "dry deposition of materials, for example, metals and inorganic salts" (Fuglsang, 2002).

2.3.2 Horizontal dust flux

Horizontal dust flux is measured by a directional gauge which collects dust from air moving in a given horizontal direction (British Standard Institute, 1972). There are a number of directional gauges used to measure horizontal dust flux, such as the British standard 1747 part 5, Sartorius (isokinetic sampler), Big Spring number eight sampler (BSNE), Suspended sediment trap sampler (SUSTRA), Modified Wilson and Cooke sampler (MWAC), Wedge dust flux (WDFG) and Dustscan.

2.3.2.1 British Standard 1747 part 5 (British Standards Institute, 1972 quoted by Fuglsang, 2002)

This gauge is equipped with four vertical tubes with a vertical slot facing towards the four points of the compass (N, S, E and W) (Galbraith and Hingston, 1991) and provides some indication of the directional character of the collected dust (figure 2.11). The gauge is installed at a selected site with dust being collected for between 28 to 33 days. The limitations of this apparatus include particle loss and inefficiency in collection of particles (Parrett, 2008). The advantages of this method include “the ability to collect sticky particles and to avoid particle bounce on the instrument. This allows the investigation of the collection of a soft or sticky particle to be conducted” (Ralph and Hall, 1989).

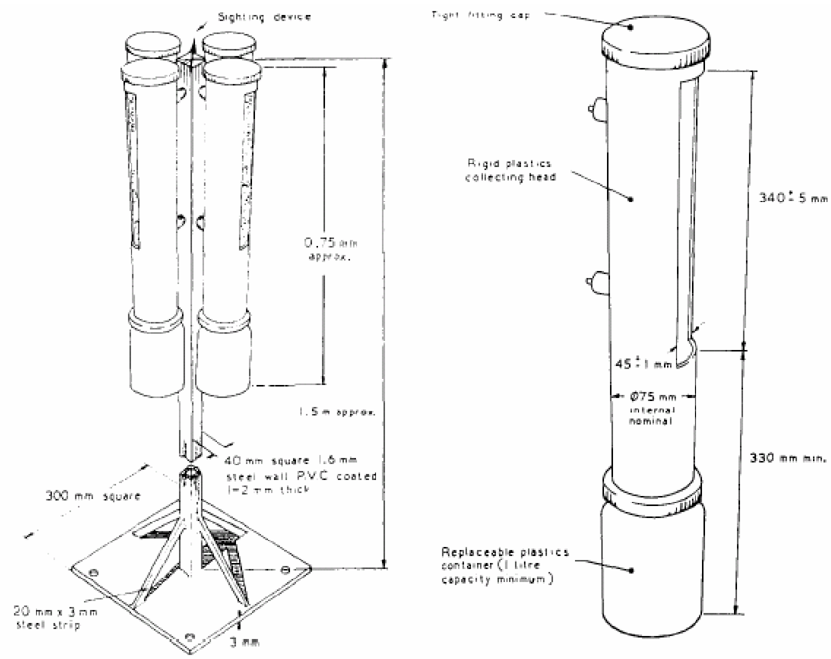


Figure 2.11: BS 1747 part 5, directional dust deposit gauge (Ralph and Hall, 1989).

2.3.2.2 Sartorius (isokinetic sampler)

The Sartorius sampler is available commercially and is an active sampler, which draws in the air at a rate that can be adjusted. Goossens (2001) states that “the dust laden air is directly sucked into a filter holder, which contains a filter with a diameter of 4 cm. The filter holder is then connected to the sample via a flexible plastic tube which allows the holder to be installed at any location of the sampler (figure 2.12). The flow discharge is adjustable between 200 and 1800 $1h^{-1}$ and the actual flow rate can be read at any time from the instrument'' (Goossens and Offer, 2000).

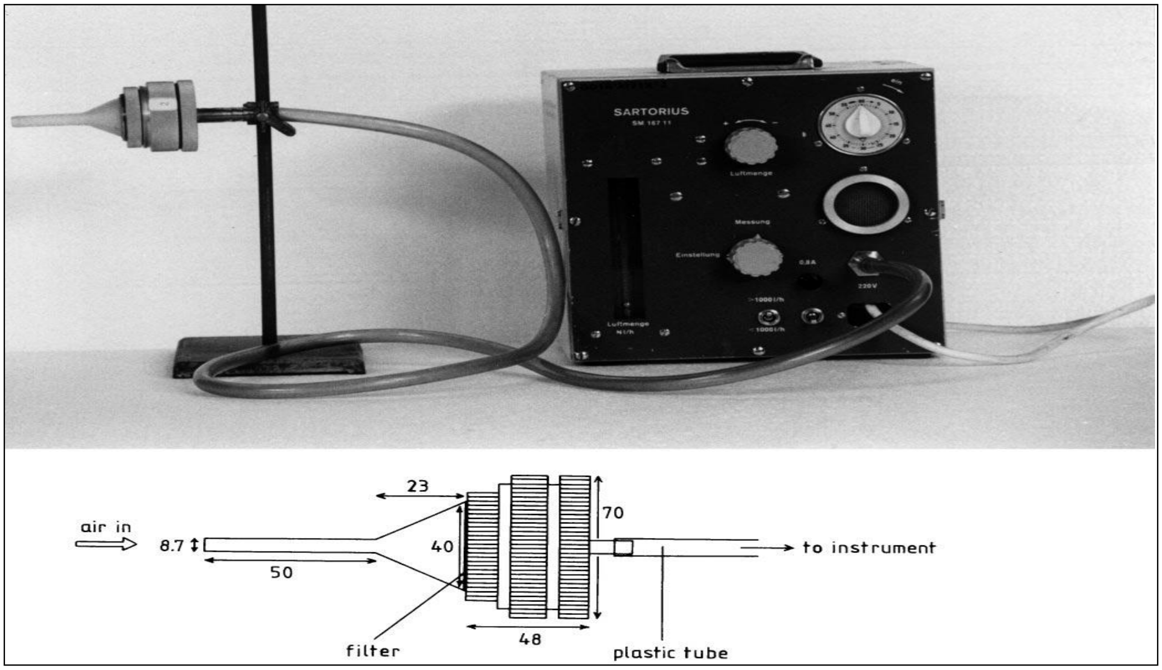


Figure 2.12: Photograph and construction scheme of the Sartorius sampler (Goossens and Offer, 2000).

2.3.2.3 Big Spring number eight sampler (BSNE)

"The Big Spring number eight sampler was developed by Fryrear in 1986. The construction of the samplers consists of a 28 gauge galvanized metal wedge, containing vertical galvanized 18-mesh screen and stainless steel 60 mesh screens. The dust laden air passes through a vertical 2 cm x 5cm sampler opening at the apex of the wedge; air speed is reduced and dust settles out on the collection pan once the sample is inside. The air is discharged through the 60 mesh screen and the 18 mesh screen which reduces the movement of deposited material, preventing the break-down of the collected sediment and potential loss of very fine particles out of the top of the screen. There is a rubber retainer which closes any small holes in the back of the sampler and the wind vane at the rear assures that the sampler is turned to the wind (figure 2.13). The efficiency for the big spring eight number sampler for 30 µm dust is always around 40% at least (varying between 35% and 45%) within the wind speed interval of 1-5 ms^{-1}" (Goossens and Offer, 2000).

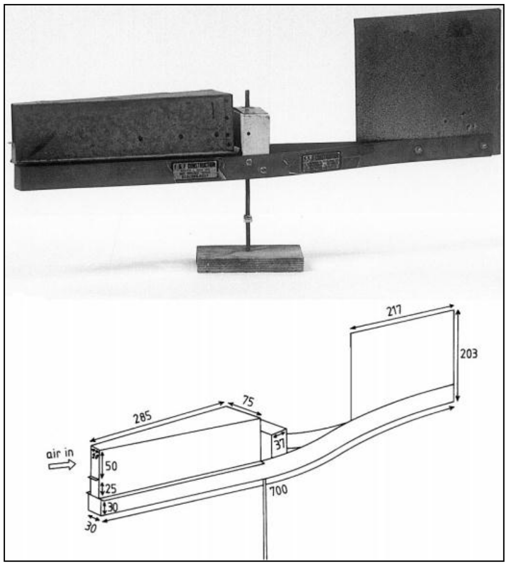


Figure 2.13: a) Photograph and construction of the BSNE sampler (Goossens and Offer, 2000).

2.3.2.4 Suspended sediment trap sampler (SUSTRA)

"The Suspended sediment trap sampler was developed by Janssen *et al*, in 1991. The sampler is used to collect different types of sediment (dust, sand and soil). The dust laden air enters the instrument via a horizontal metal tube 5 cm in diameter and rebounds onto a metal plate inside a central vertical pipe. The particles settle onto the plastic dish placed on top of the electronic balance underneath the pipe. The wind vane turns the instrument into the wind at all times. In order to minimize the airflow disturbance near the surface, the balance is placed in a metal box dug into the ground (refer to figure 2.14). The efficiency of the suspended sediment trap sampler increases with wind speed. However, even at a speed of 5 ms^{-1}, it is only 15% efficient" (Goossens and Offer, 2000).

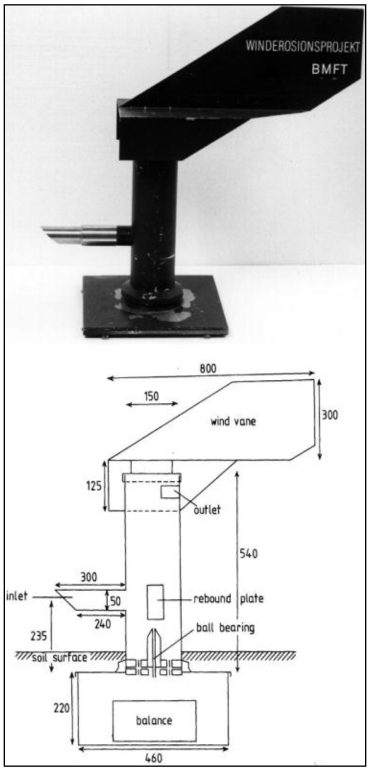


Figure 2.14: Photograph and construction scheme of the SUSTRA sampler (Goossens and Offer, 2000).

2.3.2.5 Modified Wilson and Cooke sampler (MWAC)

"The Modified Wilson and Cooke sampler was developed by Wilson *et al*, in 1980. The sampler consists of a plastic bottle, figuring as a settling chamber, to which an inlet tube and an outlet tube have been added. The bottle is installed vertically with the inlet oriented towards the wind. The sediment entering the bottle is deposited via the pressure drop created by the difference in diameter between the bottle, the inlet and outlet tubes. The inlet and outlet tubes are made of glass 1.25 mm thick with inner diameter of 7.5 mm and an outer diameter of 10.0 mm (figure 2.15). The modified Wilson and Cooke sampler has more than 90% efficiency for wind speed between 2 ms^{-1} and 5 ms^{-1} and 75% efficiency at a wind speed of 1 ms^{-1}"(Goossens and Offer, 2000).

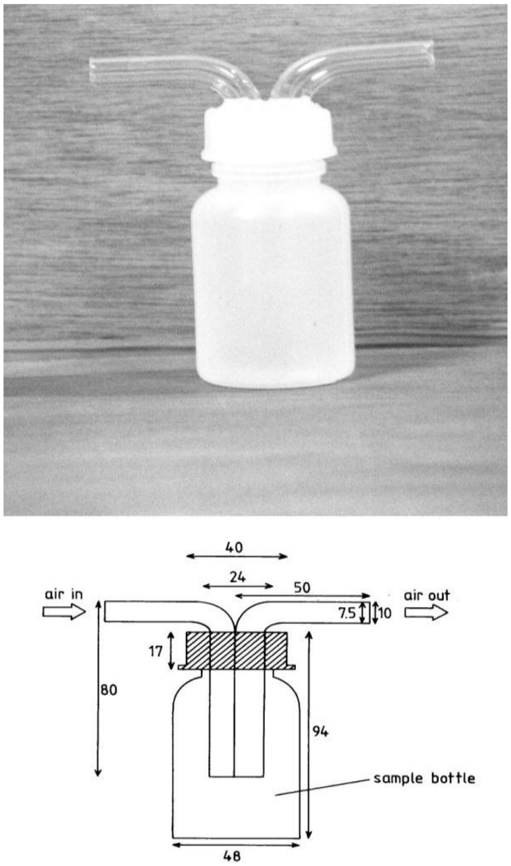


Figure 2.15: Photograph and construction scheme of the MWAC (Goossens and Offer, 2000).

2.3.2.6 Wedge dust flux gauge (WDFG)

"The Wedge dust flux gauge was developed by Hall, Upton and Marsland (1993). The sampler consists of a simple, parallel sided box, wedge shaped in elevation and with extended sides towards the rear holding a baffle plate. The flat, horizontal bottom of the box is 18 cm long and 10 cm wide and the top slopes upwards at an angle of 24.5˚. The sediment laden air enters the instrument via a 1.9 x10.0 cm rectangular slot. The box contains a particle trap made from 10 pores per inch open-celled foam which is normally sprayed with a thick sticky coating to retain any impacting particle. The maximum collection efficiency of the wedge dust flux is 63% at wind speed of 2 ms^{-1} (figure 2.16). However the efficiency will drop with an increase in wind speed" (Goossens and Offer, 2000).

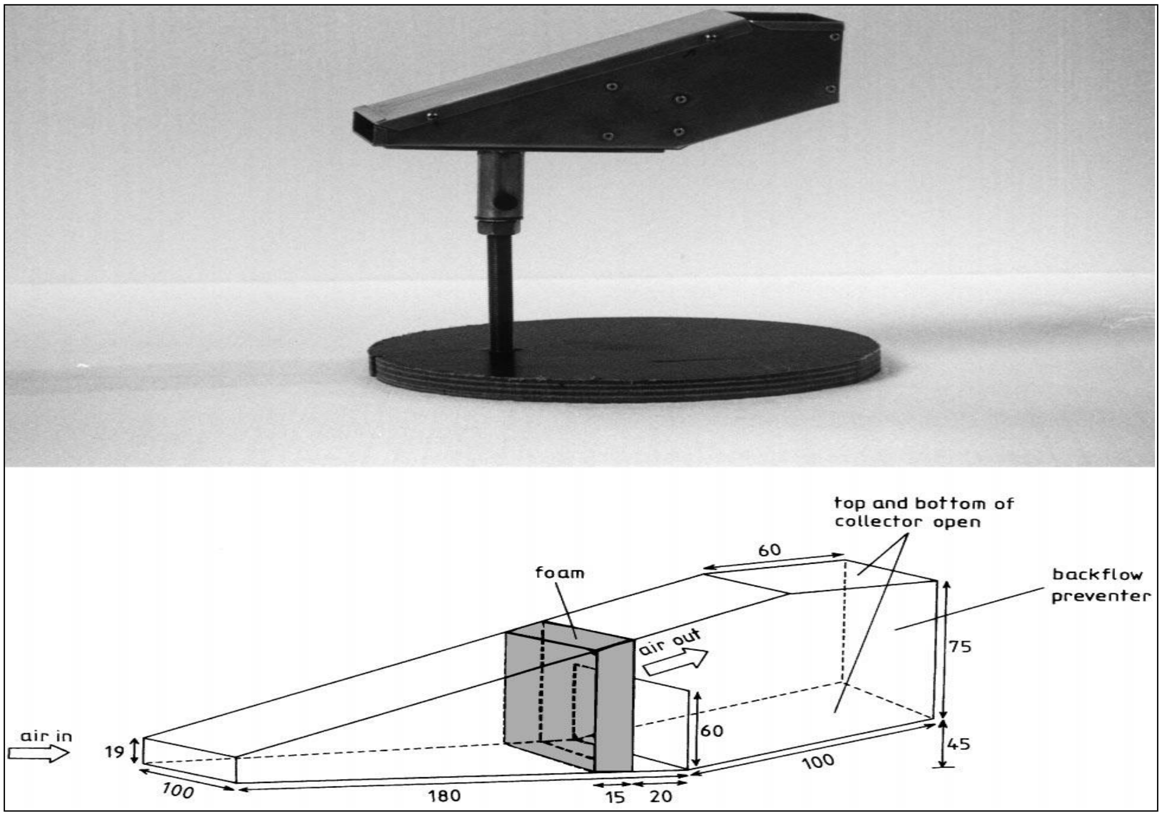


Figure 2.16: Photograph and construction scheme of the WDFG sampler (Goossens and Offer, 2000).

2.3.2.7 Dustscan

Dustscan has been developed as a low cost, directional dust monitoring system. Financial support for the technology for Dustscan was provided by the Department of Technology and Industry in the UK under the Technology Transfer Scheme (Walton, 2001 quoted by Datson, 2007). The directional dust monitoring system was designed for the mineral industry with an emphasis on affordability and reliability (figure 2.17) (Walton, 2001 quoted by Datson, 2007).

Figure 2.17: Dustscan (Walton, 2001).

The technique of the Dustscan comprises a see-through (transparent) film which an adhesive backing which is placed around a vertically-mounted cylinder that is aligned directionally. The dust borne in the air which sticks to the adhesive surface is quantified from an image file in which the scientist compares the exposed area with that of the reference area (Walton, 2001). The sticky pads have also been used to collect dust for the qualitative measurement of soiling (soiling means an act of contaminating or pollution of a substance) since the 1980s (Walton, 2001).

2.4 Comparative studies

In this section the laboratory studies and field studies of seven types of vertical deposit gauges and seven types of horizontal dust fluxes are succinctly described. The former includes unpublished results obtained by Illenberger (Illenberger, 2010) on the comparison between ASTM D1739:82 and ASTM D1739:98 and by Smith, Myles and Annegarn (2010) on comparison between ASTM D1739:82 and ASTM D1739:98. The above-mentioned dust monitoring instruments have already been shortly described in the sections 2.3.1 and 2.3.2 of this chapter.

2.4.1 Vertical dust flux

2.4.1.1. ASTM D1739

Both the studies conducted by Illenberger, 2010 and Smith *et al*, 2010 used the same dust collection and analysis method but different sites.

The collection of dust using the ASTM D1739 dust instrument was done for a period of 30 days. Distilled water and copper sulphate were added to the dust buckets to prevent algae growth. A filtration process was used to separate dust from water. The dust was then dried in an oven at 105˚C and cooled at room temperature for 24 hours. The figures below compare results obtained by Illenberger from the ASTM D1739:82 and ASTM D1739:98 at inland sites and coastal areas.

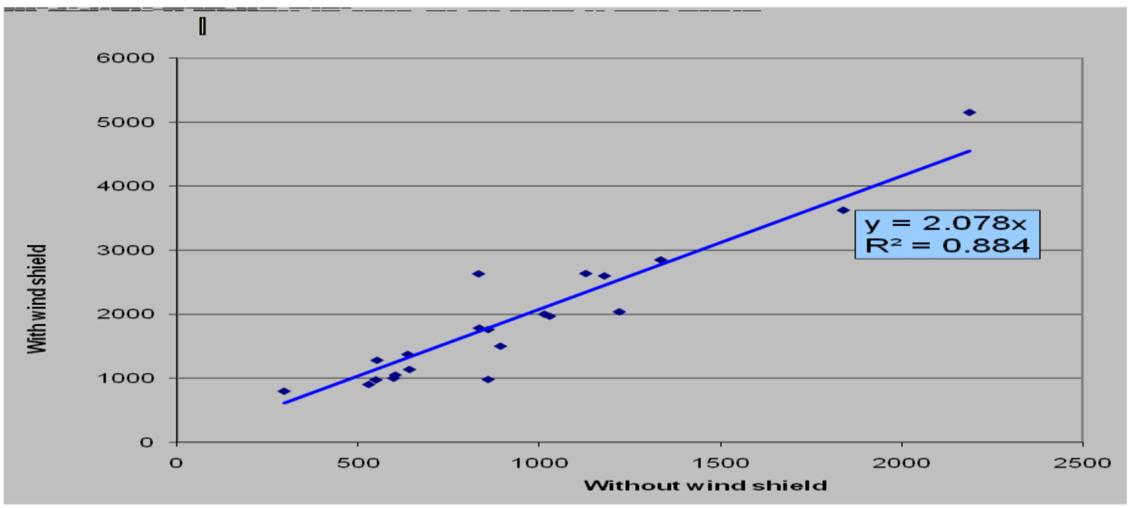


Figure 2.18: Comparison between ASTM D1739:98 (with wind shield) and ASTM D1739:82 (without wind shield) for a coastal area (Illenberger, 2010).

Figure 2.18 shows that there is a correlation coefficient of 0.884 between ASTM D1739:98 and ASTM D1739:82. The average increase in the amount of dust collected by the version with the wind shield is 107.8%.

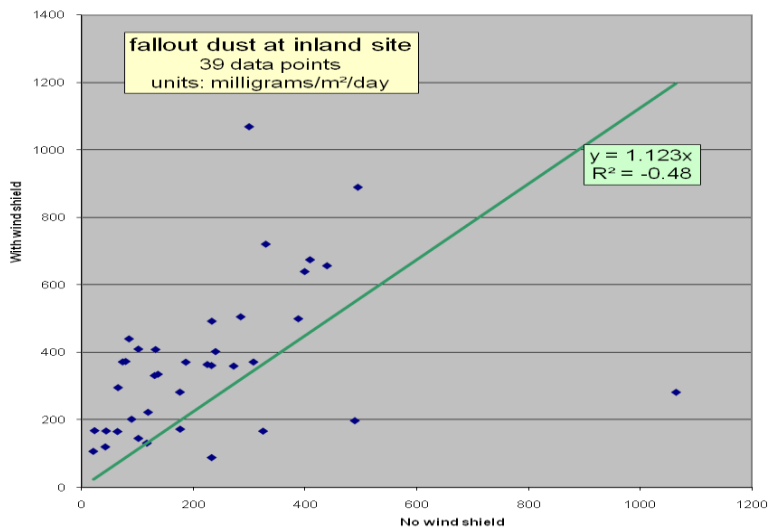


Figure 2.19: Comparison between ASTM D1739:98 (with wind shield) and ASTM D1739:82 (without wind shield) for inland site (Illenberger, 2010).

Figure 2.19 shows that there is a correlation coefficient of -0.48 between ASTM D1739:98 and ASTM D1739:82 (Illenberger, 2010) (The negative number is an artifice of the Microsoft Excel correlation software used by Illenberger when the line is forced to pass through the origin of the graph). The average increase in the amount of dust collected by the version with wind shield is 12.3%. It should be noted, for comparison with results obtained in the present study, that the results for the inland site have a much lower average deposition rate than the coastal site results. Also, if the outliers were removed, the slope of the correlation line will be considerably higher for the inland site comparison.

Smith *et al*, (2010) provide a comparison between ASTM D1739:82 and ASTM D1739:98 for a gold mine and a coal mine as shown in figures 2.20 and 2.21 below.

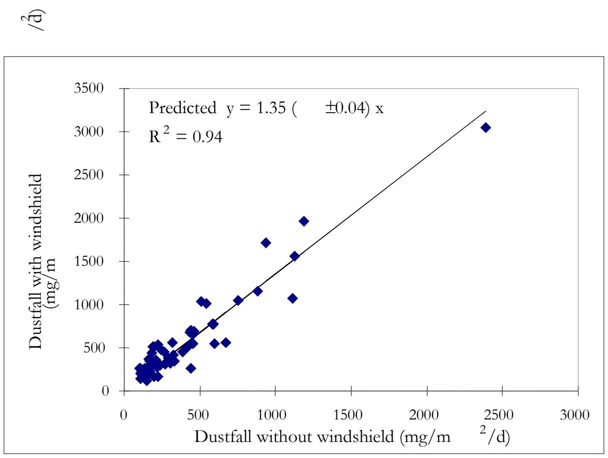


Figure 2.20: Correlation plot ASTM D1739:98 with wind shield and ASTM D1739:82 without wind shield for surface gold mine reclamation site (Smith *et al,* 2010).

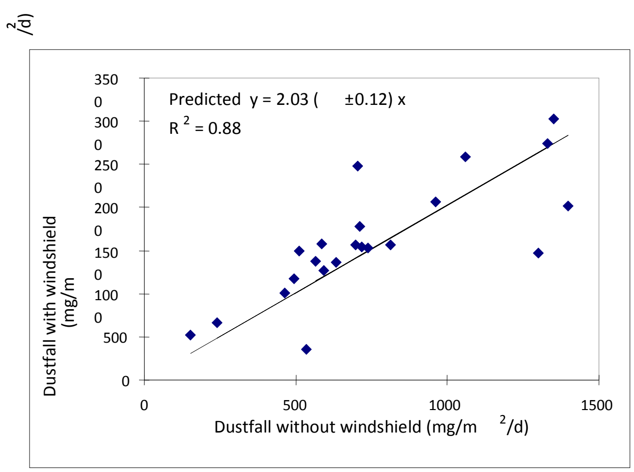


Figure 2.21: Correlation plot between ASTM D1739:98 with wind shield and ASTM D1739:82 without wind shield for coal-mining site AR4 (Smith *et al,* 2010).

Table 2.1: Regression coefficients from comparing gold reclamation mine site and surface coal mine site AR4 (Smith *et al,* 2010).

Regression Statistics		
	Gold	*Coal*
Multiple R	0.98	0.96
R Square	0.95	0.93
Adjusted R Square	0.94	0.88
Standard Error	163	469
Observations	59	22
Intercept	0.00	0.00
Coefficient	1.35	2.03
Standard Error	0.04	0.12
t-stat	34.40	16.71
Significance level	95%	95%
P-value	<0.01	<0.01

From figures 2.20 and 2.21 and from the summary in table 2.1 one can deduce that there is a distinct increase in dust deposition using the wind shield, significant at the 95% level with P-value <0.01. The regression lines were constrained to pass through zero (Smith *et al,* 2010). The slope coefficient for the gold mine sites is 1.35, indicating that the wind shield increases the dust deposition by 35% relative to the sampler without the wind shield; for coal the slope coefficient is 2.03, indicating an increase of 103%. The mean slope of the two test series (not weighted for the number of samples) is 1.69, equivalent to a 69% increase in dust deposition (table 2.1). It is again clear that both the regression coefficient and the slope of the regression line increase as the deposition rate increases.

2.4.1.2 Field studies of other vertical flux monitors

Hall (1994; 1988) investigated monitoring deposited dust using the function of wind speed and particle size by using the BS 1747 part 1 deposit gauge as a sampler. Dust was collected in a dust bucket using BS 1747 part 1 deposit gauge for a sampling period of 28 to 33 days. "Material deposited by dust deposited material is separated from the liquid by mild vacuum filtration and dried in the drying oven" (ASTM International, 2010). The dust deposition rate was calculated and results were expressed as mg/m^2-day (figure 2.22). When the wind speed increases, the efficiency decreases.

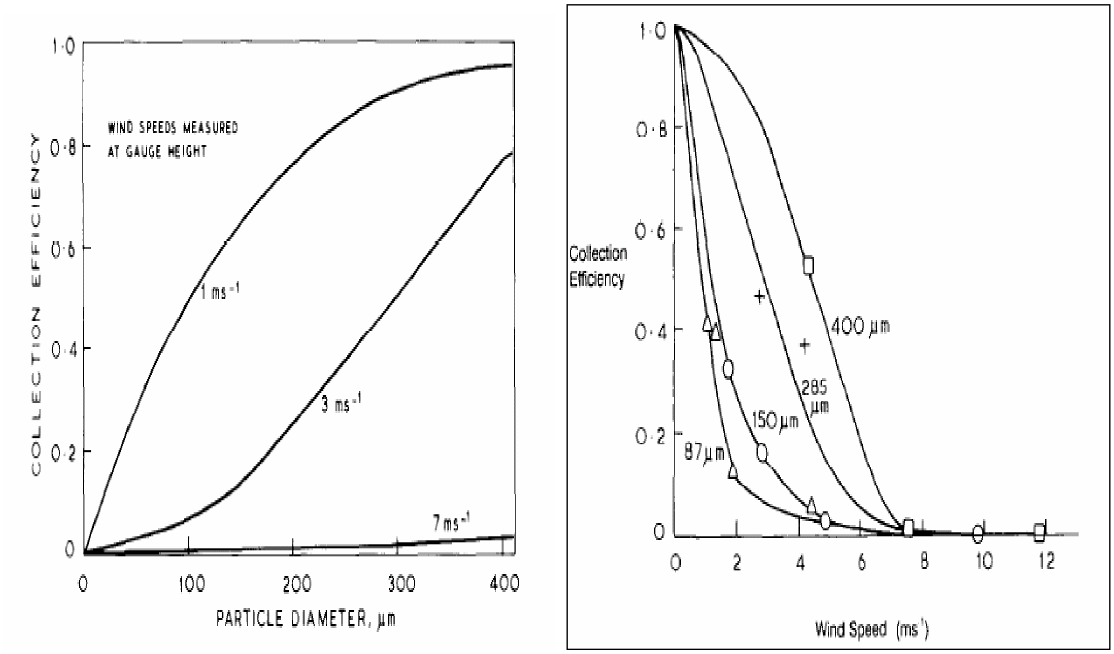
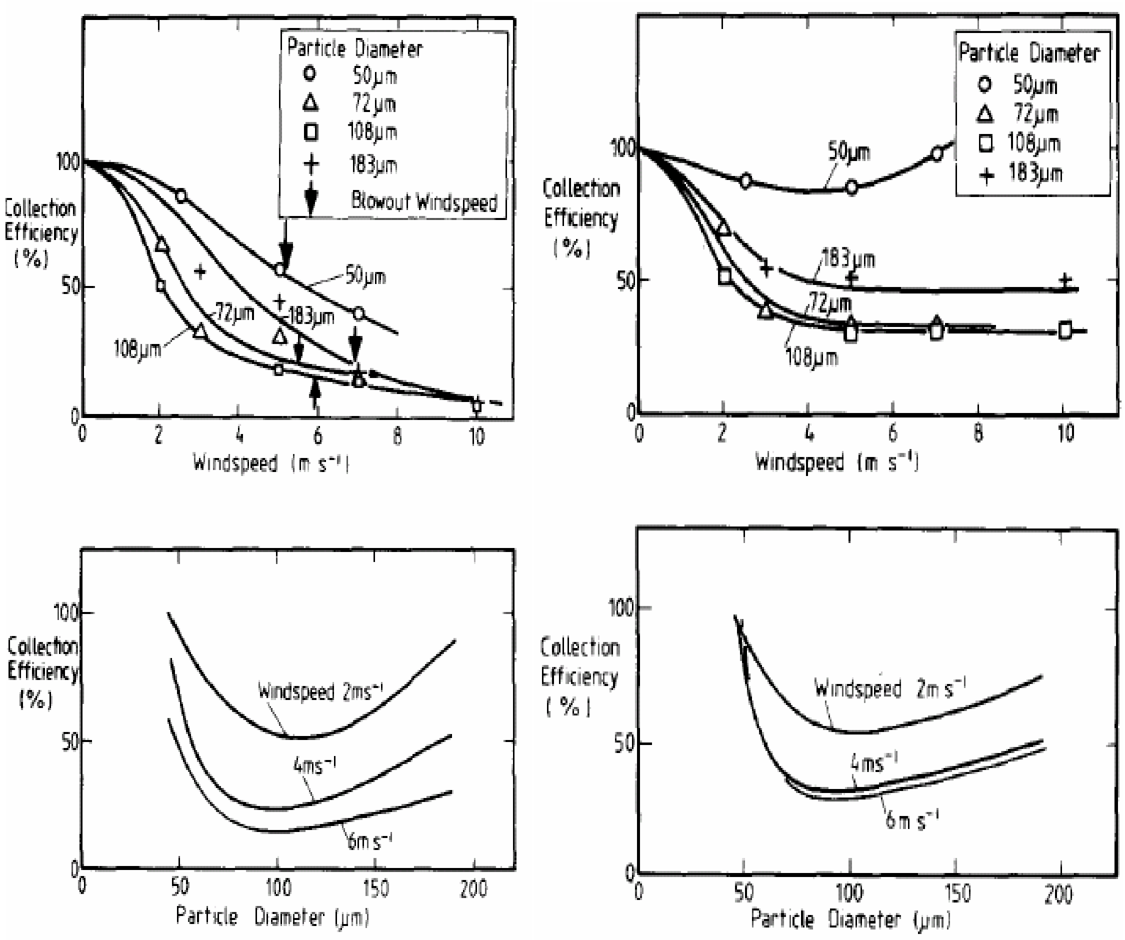


Figure 2.22: The collection efficiency of the deposit gauge versus particle diameter and wind speed (Hall 1988 quoted by Dombrowski, Foumeny, Ingham and Qi, 1996).

Hall (1988) quoted by Dombrowski, Foumeny, Ingham and Qi (1996), investigated the performance of the different versions of the frisbee dust deposit gauge. Dust collected in Kortbeek-Dijle, Belgium was used. After exposure of the collectors, “the content of the bottle used for collecting was filtered under suction using a Whatman 3 - piece funnel leading into a 1 liter Buchner flask” (Hall and Upton, 1988). Leaves or bird droppings inside the funnel were removed. Filter paper was weighed before it was used to separate dust from water. After drying the filter paper was re-weighed to calculate the dust deposition rates. “The efficiency was calculated for grain size classes ranging 10-19 µm, 19-31 µm,32-41 µm,41-48 µm,48-56 µm,56-66 µm,66-76 µm and 76-89 µm” (figure 2.23 a and b) (Hall and Upton,1988).



a b

Figure 2.23 a) Collection efficiency of uncoated frisbee as a function of wind speed and particle size; b) Collection efficiency of coated frisbee as a function of wind speed and particle size (Hall and Upton, 1988).

The results from Dombrowski *et al* (1996) showed that the efficiency of dust collection decreases with increasing wind speed as shown in figure 2.23 a. The effect of particle size becomes more pronounced as particle size increases above 50 µm; coating of the frisbee surface mitigates the effect of both wind speed and particle size.

Vallack and Shillito (1995) carried out comparative field tests between the British Standard 1747 part 1: vertical dust deposit gauge and the frisbee dust deposit gauge. It was impracticable to carry out full collection efficiency measurement over "the measurements of dust deposition were therefore made at four fixed conditions: two different wind speeds and two different particle sizes. At higher wind speed the collection efficiency falls markedly for all particles sizes. The

British Standard 1747 part 1 and dry frisbee results are displayed in the form of a correlation graph" (figure 2.24) (Vallack and Shillito, 1995).

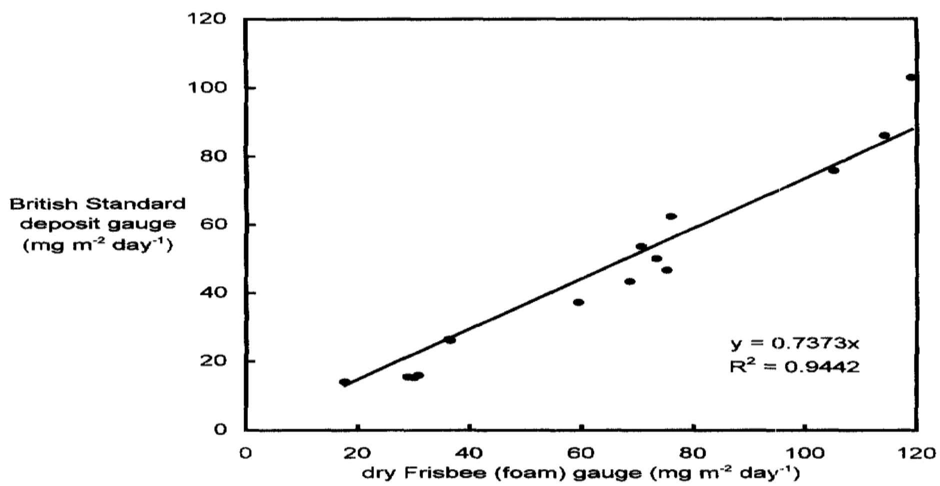


Figure 2.24: Linear regression of monthly dust rates shows comparisons between British standard deposit and Frisbee gauge (Vallack and Shillito, 1995).

Vallack and Shillito (1995) show that results for the British Standard 1747 part 1 deposit gauge and dry frisbee gauges are highly correlated, and that the dry frisbee collects 36% more dust than the British Standard 1747 part 1 gauge.

The efficiencies of four forms of the modified inverted frisbee have also been tested (Sow *et al*, 2006) (see figure 2.25 and figure 2.26). "The versions are the inverted frisbee which lacks the marbles and a ring, the inverted frisbee without marbles and with a ring, the inverted Frisbee which has marbles yet is without a ring and the inverted Frisbee with both the marbles and a ring" (Sow *et al*, 2006).

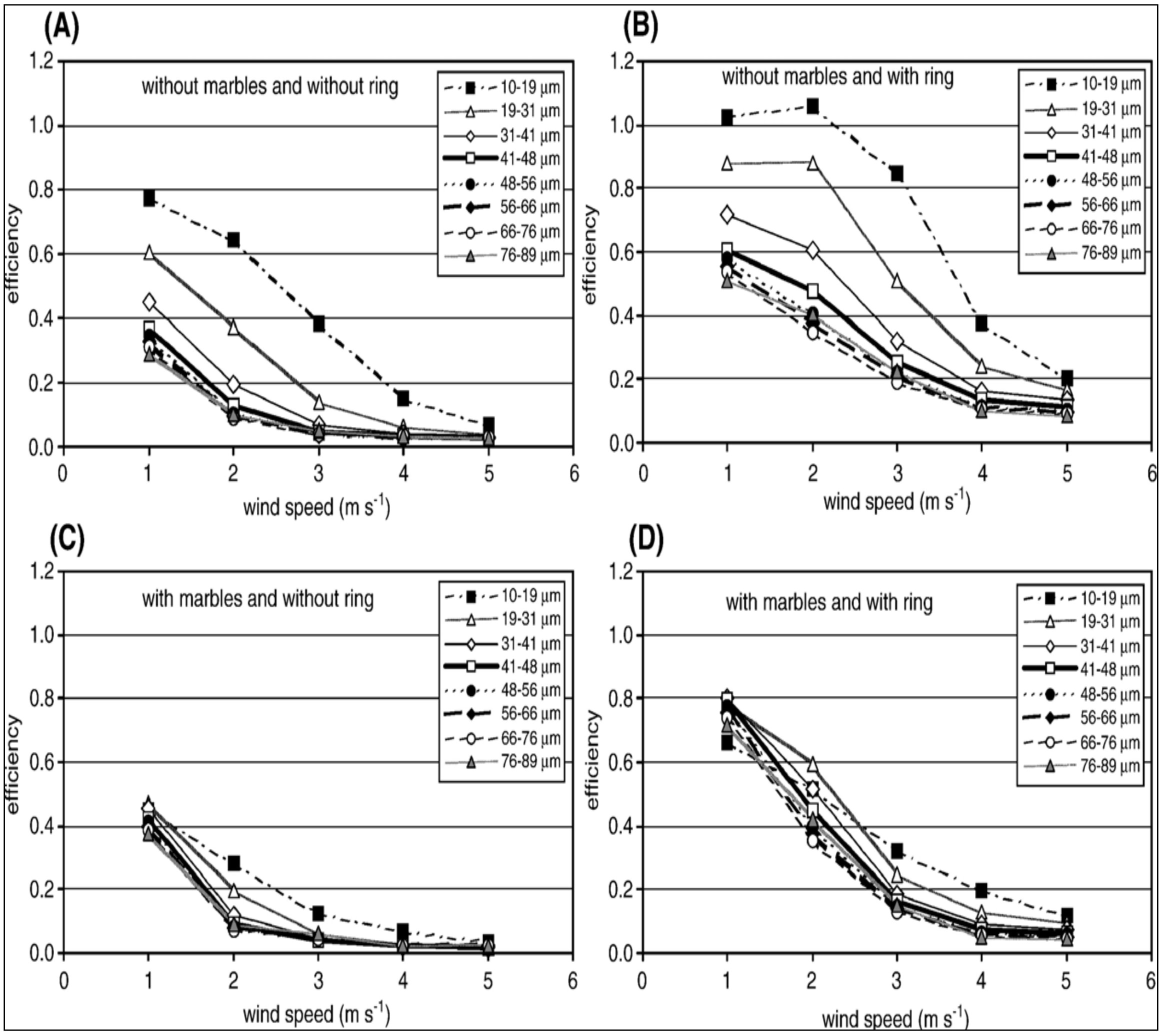
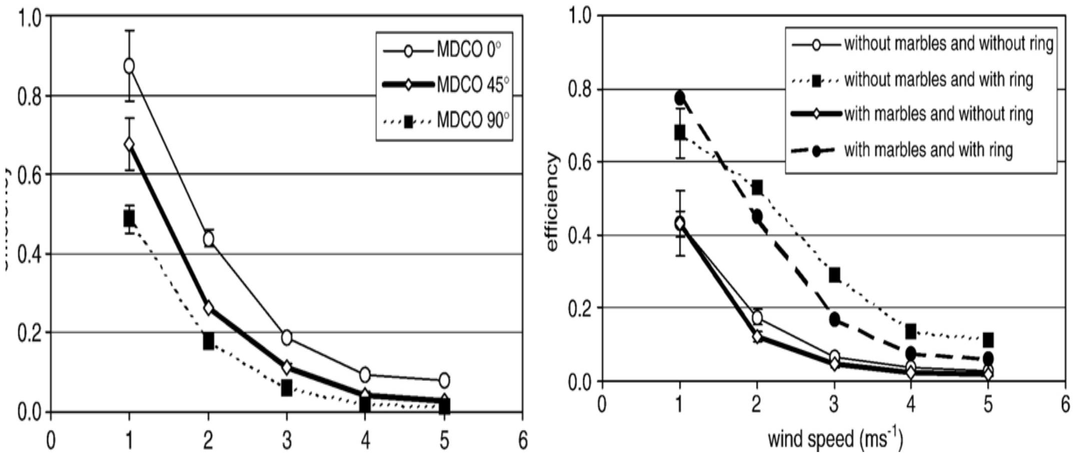


Figure 2.25: Efficiency of inverted frisbee as a function of grain size (Sow *et al*, 2006).

In general terms, the results confirmed those found by Dombrowski *et al* (1996), with exception of unexpected result that the addition of marbles reduced the efficiency.

Sow *et al* (2006) investigated the measurement of the vertical dust flux using a rectangular Marble dust collector sampler (MDCO) (figure 2.26). The orientation effect with respect to the wind was tested by setting up at 0˚, 45˚ and 90˚ to the wind. “The dust sample was determined with precision by weighing the sampler (with the marbles) before and after the analysis”.



Wind speed (ms^{-1}) **Wind speed (ms^{-1})**

a b

Figure 2.26 a) MDCO collecting efficiency for total sediment as a function of wind speed; b) inverted frisbee (Sow *et al*, 2006).

Figure 2.26 (a) on the left illustrates that the highest efficiency is obtained for a MDCO at 0° to the wind.

The comparison in the right of figure 2.26 b) shows that the efficiency of an empty frisbee is most commonly lower than of an MDCO.

Fuglsang (2002) investigated the determination of dust deposition rates using a wind sensitive sampler (Metdust). "The collection time used for sampling was a month (30 days) and the sampling was performed at two different sites during the field test. The collected particles were separated by filtration. The insoluble fraction of dust was then established and bulk deposition rates calculated" (Fuglsang, 2002).

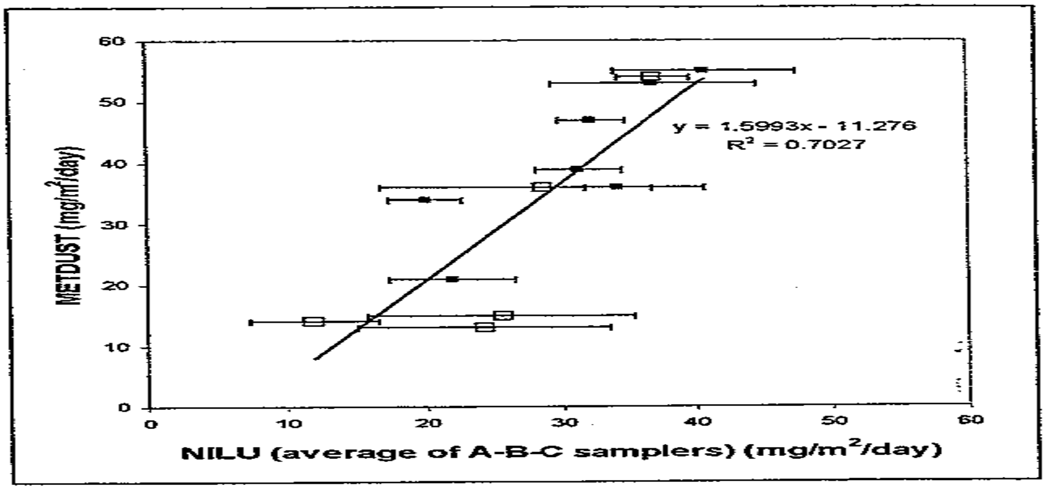


Figure 2.27: Comparisons between Metdust and Nilu (Fuglsang, 2002).

Figure 2.27 shows that, in general, the Metdust results are lower than the Nilu at low deposition rate of <20 mg/m^2-d (Fuglsang, 2002). However, at dust deposition rates in the run of 20 to 40 mg /m^2-d, the Metdust results are as much as 30% higher than the Nilu results (Fuglsang, 2002).

2.4.2 Horizontal dust flux

BS 1747 part 5 investigated the performance of the horizontal dust flux gauge according to BS 1747 part 5 for dust particles of various sizes as a function of wind speed. "After collection of the dust, an aqueous suspension of the dust was placed in a glass cell filled with water and dust loading was estimated by the amount of obscuration observed when a beam of light was passed through the cell. Or in an alternative instance, insoluble deposited material was filtered, dried and determined gravimetrically. The findings were expressed in units of mg/m^2-day for each direction" (Hall, 1994 quoted by Mineral Industrial Research Organization, 2011) (see figure. 2.28 below).

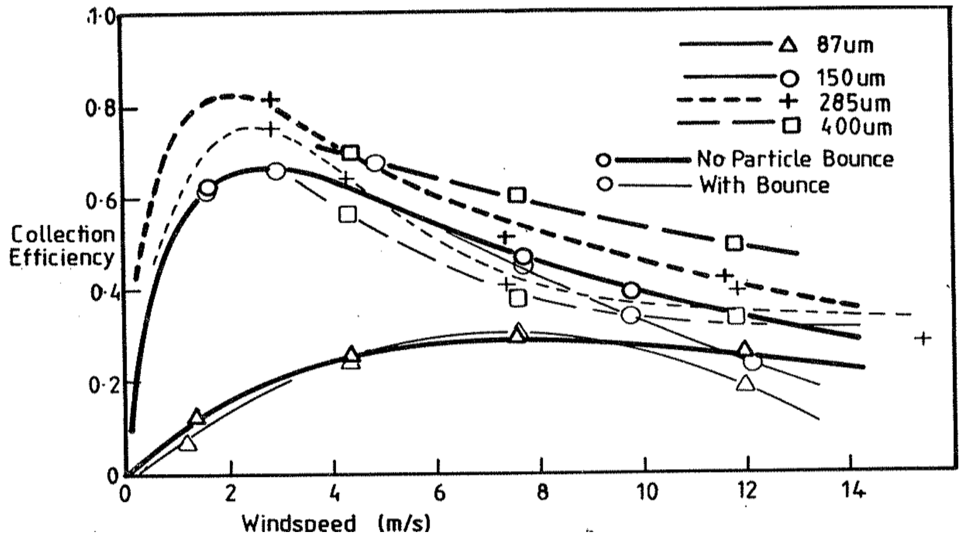


Figure 2.28: Collection performance of the British standard directional dust gauge with four particle sizes (Hall, 1994).

The performance between four particles which relays on the wind speed for the movement in the atmosphere. The wind speed effect depends on the particle size (Galbraith and Hingston, 1991). The reason for the reduction in efficiency with increasing wind speed is that internal wind circulation inside the cylinder tube increases with wind velocity. This pushes the trapped particles out of the gauge body. The overall collection efficiency of the BS directional dust gauge is low (Hall, 1994).

Goossens and Offer (2000) investigated measurement of horizontal dust flux using a comparative study between Big Spring number eight sampler (BSNE), the Modified Wilson and Cooke sampler (MWAC), the Suspended sediment trap sampler (SUSTRA) and Wedge dust flux gauge (WDFG) using both field and wind tunnel testing. A Sartorius sampler was made operative in close proximity to other samplers to avoid any mutual interaction and was used as the reference sampler. It operates freely by rotating and turning itself to the wind” (Goossens and Offer, 2000).

Results for the BSNE, at that time "one of the most frequently used samplers in dust research" (UCL, 1999), are shown in figure.2.29 below.

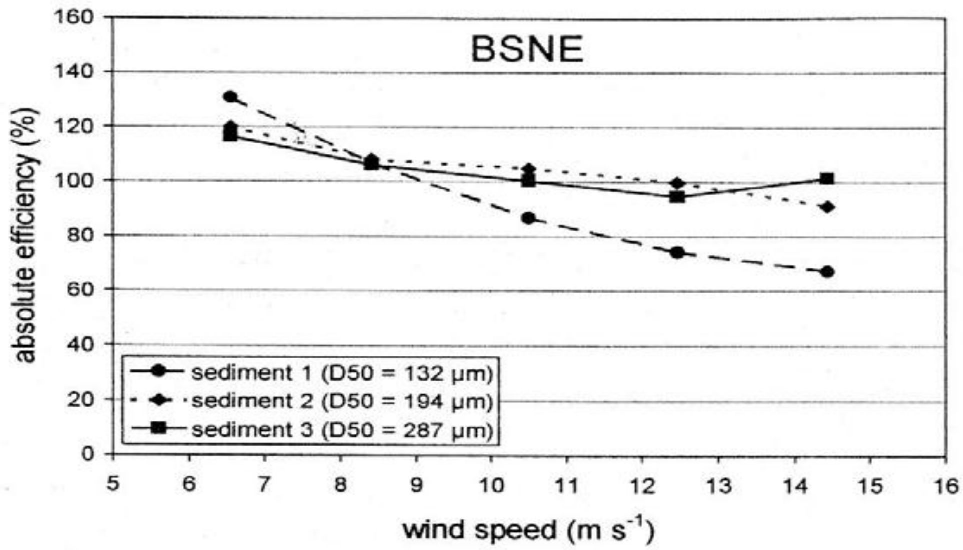


Figure 2.29: Absolute efficiency of the BSNE (Goossens and Offer, 2000 quoted by Blanco-Canqui and Lal, 2008).

The absolute efficiency of the BSNE ranges from 62-132%. The efficiency becomes less as the wind speed increases.

Results obtained for the SUSTRA are shown in figure 2.30 below.

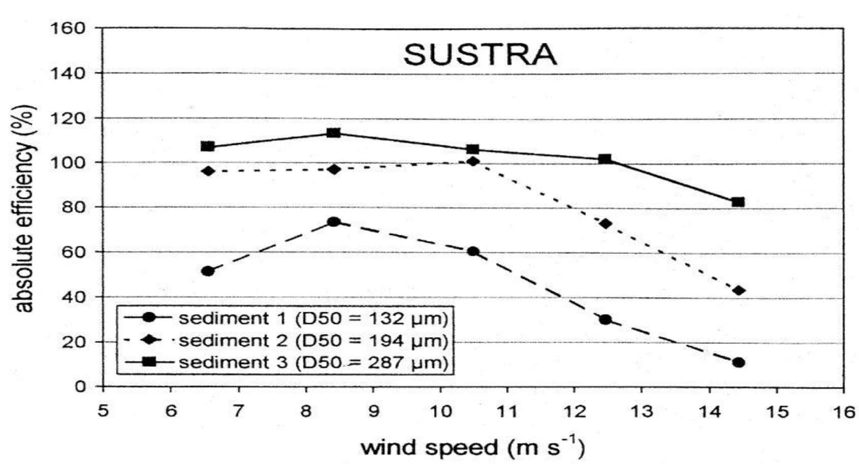


Figure 2.30: Absolute efficiency of the SUSTRA (Goossens and Offer, 2000 quoted by Blanco-Canqui and Lal, 2008).

The efficiency systematically decreases with wind speed.

Results for the Modified Wilson and Cooke sampler are shown in figure 2.31 below.

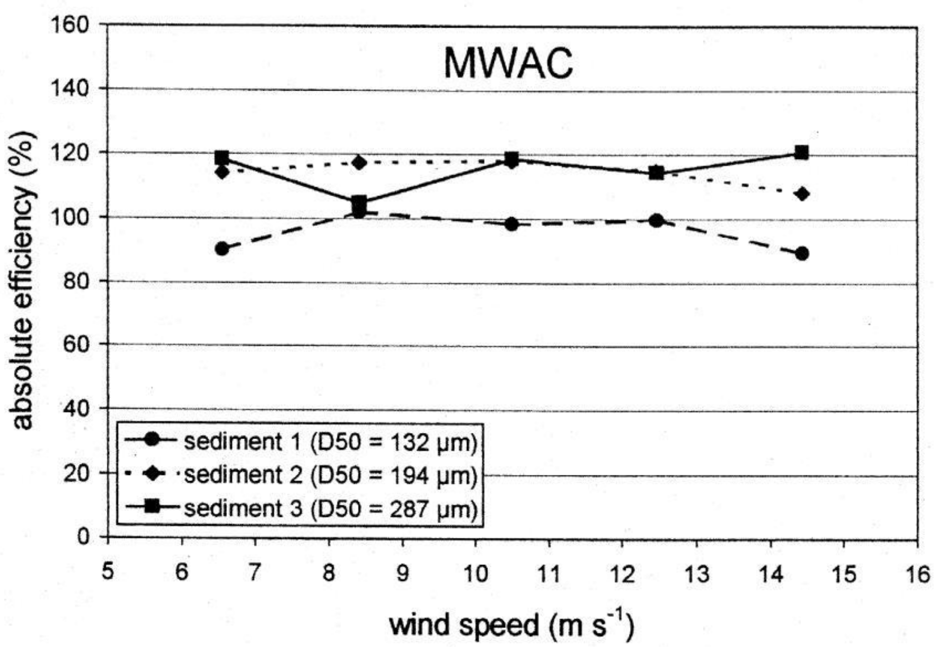


Figure 2.31: Absolute efficiency of MWAC (Goossens and Offer, 2000).

"Overall, results show that the sample which is the most efficient is the MWAC", which shows consistent efficiencies over 75% (UCL, 1999). The MWAC is however not recommended by Goossens and Offer (2000) mostly due to its variable efficiency values at very low velocities, but it is still a very good alternative. "The absolute efficiency for sand between 132 µm and 287 µm is always between 90% and 120%" (UCL, 1999).

"The field ranking and the wind tunnel ranking of the samplers are exactly the same in spite of the relatively small variations in mean wind speed" (UCL, 1999). BSNE has the second efficiency ranking following MWAC but it is still a quite good measurement sampler. SUSTRA is similar to BSNE sampler. For many of the instruments the efficiency increases with sediment particle size. The SUSTRA sampler is not recommended since its efficiency curve varies considerably with particles sizes and it is the least efficient of the five samplers (Goossens and Offer, 2000).

Walton (2001) investigated the measurement of nuisance dust around the mineral workings using the Dustscan. The sticky pads were prepared from material that is easily obtainable (stock material). The sticky pads components comprise the transparent film, adhesive, backing and sealing sheets. The sample area is left bare while the reference area and the three edges of the sticky pads are covered by the backing paper. Thus, the sample area is surrounded by clean, unexposed adhesive so that the dust sample can be completely encapsulated when brought from the field (Walton 2001 quoted by Datson, 2007). Dustscan software was used to analyse the dust results using two measures for the amount of dust collected (Walton, 2001).

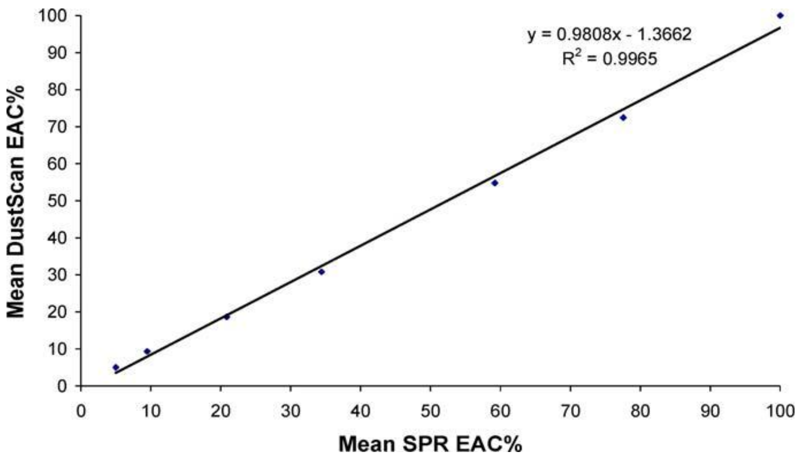


Figure 2.32: "Scatter plot showing relationship between mean Sticky pad reader (SPR)-generated Effective area coverage (EAC) % and mean Dustscan-generated EAC% values for 7 shades of grey in printed test cards" (Datson, 2007).

Figure 2.32 demonstrates that there is a very high degree of correlation between the two methods. Furthermore, consideration of AAC% (Absolute area coverage) and EAC% (Effective area coverage) values are both useful in identifying dust sources (Datson, 2007). It was found that a high level of light-coloured dust may have high AAC% and low EAC%; a low level of dark-coloured dust may have moderate AAC% and high EAC% (Datson, 2007).

2.5 Development of standards

2.5.1 Definition of a standard

A standard "is a published specification that establishes a common jargon and includes a technical specification or other exact criteria and is intended to be used without variation, as a rule, a guideline, or a definition. Standards are used in application to many materials, products, methods and services. They assist in simplifying everyday life and enhance the reliability and the effectiveness of many materials and services used in society. The standards are designed to be used voluntarily by individuals or organisation and do not impose any regulations. However, legislation and formal regulations may refer to standards and enforce compliance with them thus making them compulsory" (Standards Australia Limited, 2010).

2.5.2 South African deposition guidelines and standards

SANS 1929-2005 describes the proposed guideline criteria for vertical dust deposition. Four band scales are used to set target, action and alert threshold concentrations for dust deposition, in addition to permissible margins of tolerance and exceptions. The four band deposition criteria, extracted from SANS 1929-2005 are shown in table 2.2. The dust deposition rates are expressed in units of mg/m^2-d over a 30 day averaging period (State of Air Report, 2009).

Table 2.2: Evaluation criteria for dust deposition (SANS 1929:2005).

Band number	**Band description label**	**Dust fall rate D (mg/m^2-30 day average)**	**Comment**
1	Residential	D <600	Permissible for residential and light commercial
2	Industrial	600 < D < 1200	Permissible for heavy commercial and industrial
3	Action	1200 < D < 2 400	Requires investigation and remediation if two sequential months lie in this band, or more than three occur in a year
4	Alert	2400 < D	Immediate action and remediation required following the first incident of the dust fall being exceeded. Incident report to be submitted to the relevant authority.

"In terms of the proposed dust fall out limits, an organisation or endeavor may put a request forward to the authorities to carry out operations within the 'Band 3

Action' range for a limited period, provided that this is necessary for the practical operation of the enterprise (e.g., to accommodate the final removal of a tailings deposit), and provided that optimal control technology available to the enterprise is applied for the period of time. No margin of tolerance is permitted for operations that result in dust fall rates in the 'Band 4 Alert' range. Table 2.3 below shows the action levels for average dust deposition rates (State of Air Report, 2009).

Table 2.3: Target, action residential, action industrial and alter threshold for ambient dust fallout (SANS 1929:2005).

Level	Dust fall rate ,D (mg/m^2-d) 30 day average)	Average period	Permitted frequency of exceeding dust fall rate
Target	300	Annual	
Action residential	600	30 days	Three within any year, no two sequential months
Action industrial	1200	30 days	Three with any year, not sequential months
Alert threshold	2400	30 days	None. First incidence of dust fall rate being exceeded requires remediation and compulsory report to the relevant authorities

"For heavy commercial and industrial regions, the guidelines state that monthly average dust deposition rates below 1200 mg /m^2 - d are permissible. The 1200 mg / m^2 -d per threshold levels have typically been used in practice to indicate what action is required. Exceeding this dust deposition rate indicates the necessity of inquiring into the exact causes of high dust fall and of taking action to remediate the situation. Areas recording monthly average dust deposition concentrations between 1200 mg/m^2-d and 2400 mg/m^2-d require further investigation and remediation. Areas recording monthly average dust deposition concentrations that exceed 2400 mg/m^2-d will require immediate action and remediation and an incident report has to be issued to the relevant authority" (State of Air Report, 2009).

CHAPTER THREE: STUDY METHODOLOGY

3.1 Introduction

This chapter discusses the methodology adopted for the research. It gives the description of planning, selection of sampling sites, sampling and analysis of dust samples. Furthermore this chapter gives a brief description on how the results were processed, interpreted and the tool or method used to interpret the results.

3.2 Planning

The planning entailed the determination of criteria to select the study area and the identification of monitoring points at the study site. More than one gauges has been set up at each site using the settings recommended in the corresponding standards (ASTM D1739:82, ASTM D1739:98, BS 1747 Part 5).

3.3 Selection of sampling sites and contaminants of concern for the study

Two sampling sites per mine (i.e. an area of high level and area of low level of dust deposition) for the coal and gold mine were selected (see table 3.1).

Table 3.1 Sampling sites for high dust deposition rate and low dust deposition rate.

Name of the mine	Sites per mine	High or Low	Coordinates	
Driefontein mine: North-West province	East village recreational club	Area of low deposition	26°23’12.1’’S	27º30’50.9’’E
Driefontein mine: North-West province	Leslie williams hospital	Area of high deposition	26º24’11.1’’S	27º25’ 40.9''E
Kleinkopje colliery mine:Mpumalanga province	Ericson dam	Area of low deposition	26º24’30.7’’S	27º25’21.4’’E
Kleinkopje colliery mine:Mpumalanga Province	Tip area	Area of high deposition	26º00’55.3’’S	27º13’34.7’’E

3.3.1 Study areas

“Driefontein mine which is located at about 70 km west of Johannesburg at latitude 26˚24’03.7”S and longitude 27˚25’24.1”E close to Carletonville in North-West Province, South Africa. The N12 highway between Johannesburg and Potchefstroom is where the site is accessed (Goldfields, 2007; 2008).

The mine consists of seven gold producing shaft systems and the other three gold plants namely: 1) Plant produce most underground ore, 2) the plant produces both underground ore as well as surface material, 3) the plant produce surface material only (Goldfields, 2007; 2008).

The mine is geologically situated in the West Wits Line Goldfield of the Witwatersrand Basin. There are three primary ridges that are exploited namely the Ventersdorp Contact Reef (VCR) which is situated at the top of the Central Rand Group, the Carbon Leader Reef (CL) situated close to the base and the Middelvlei Reef (MR), which stratigraphically happens some 50 metres to 75 metres above the CL (Goldfields, 2007;2008). The two sampling sites are indicated on the map namely East Recreational Village Club and Leslie Williams (see figure 3.1).

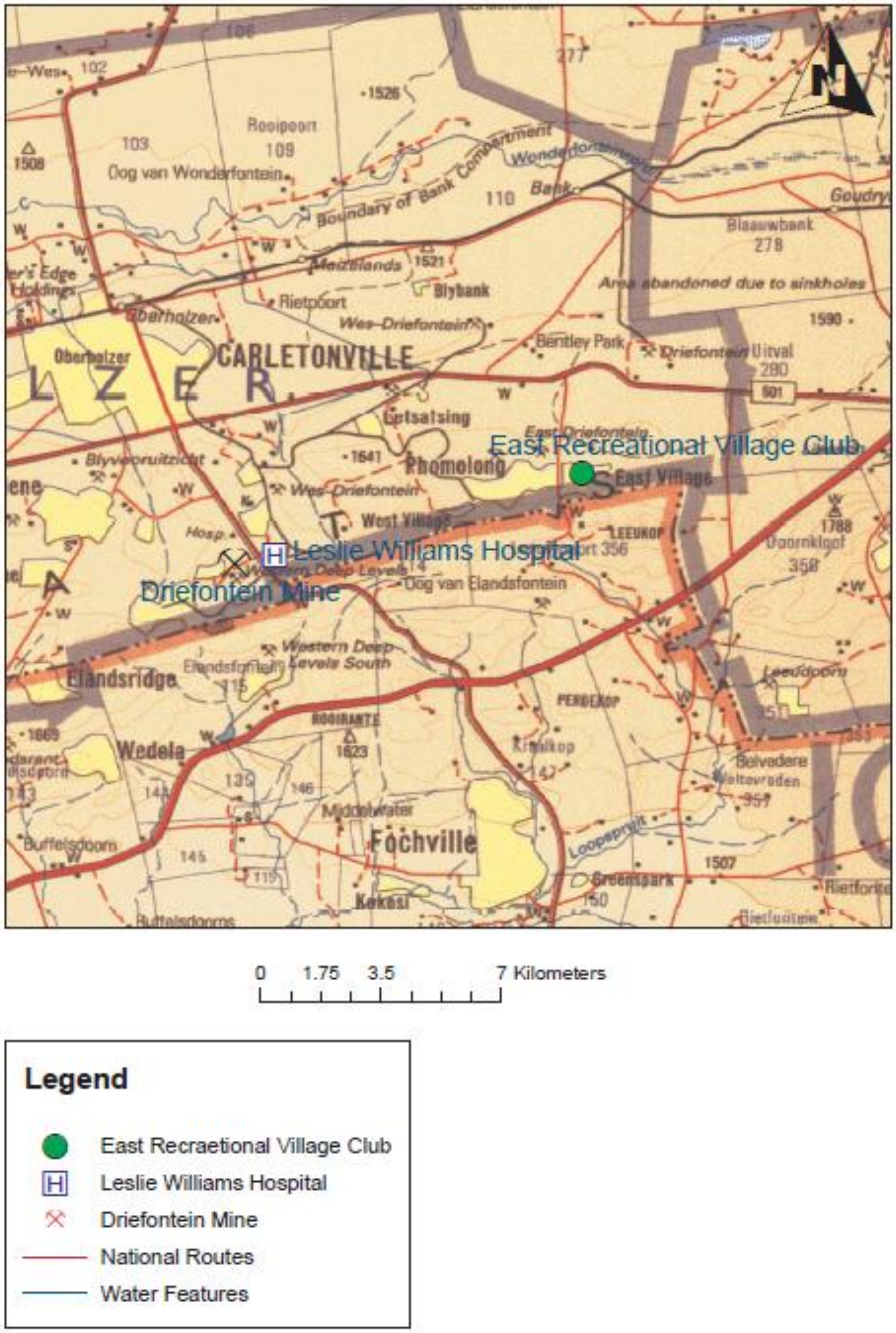


Figure 3.1: Sampling locations for Driefontein mine near Carletonville.

“Kleinkopje colliery mine is located 10 km south-west of eMalahleni at latitude 26˚ 32’12.1”S and longitude 27˚30’50.9”E in Mpumalanga Province, South Africa (Tamenti, 2007). The area is characterized by numerous coal mines and various mineral industries. Kleinkopje colliery mine is one of AngloCoal South Africa’s export mines and has been in operation for 32 years. It produces coal for pulverized fuel injection in local power stations and also exports thermal coal. The domestic markets and metallurgical coal for consumption by the local steel industry are process from washed and sized coal” (Anglo Coalfields, 2010). The two sampling sites at this mine are indicated on the map which shows Ericson dam and Tip area in Kleinkopje colliery mine. See figure 3.2.

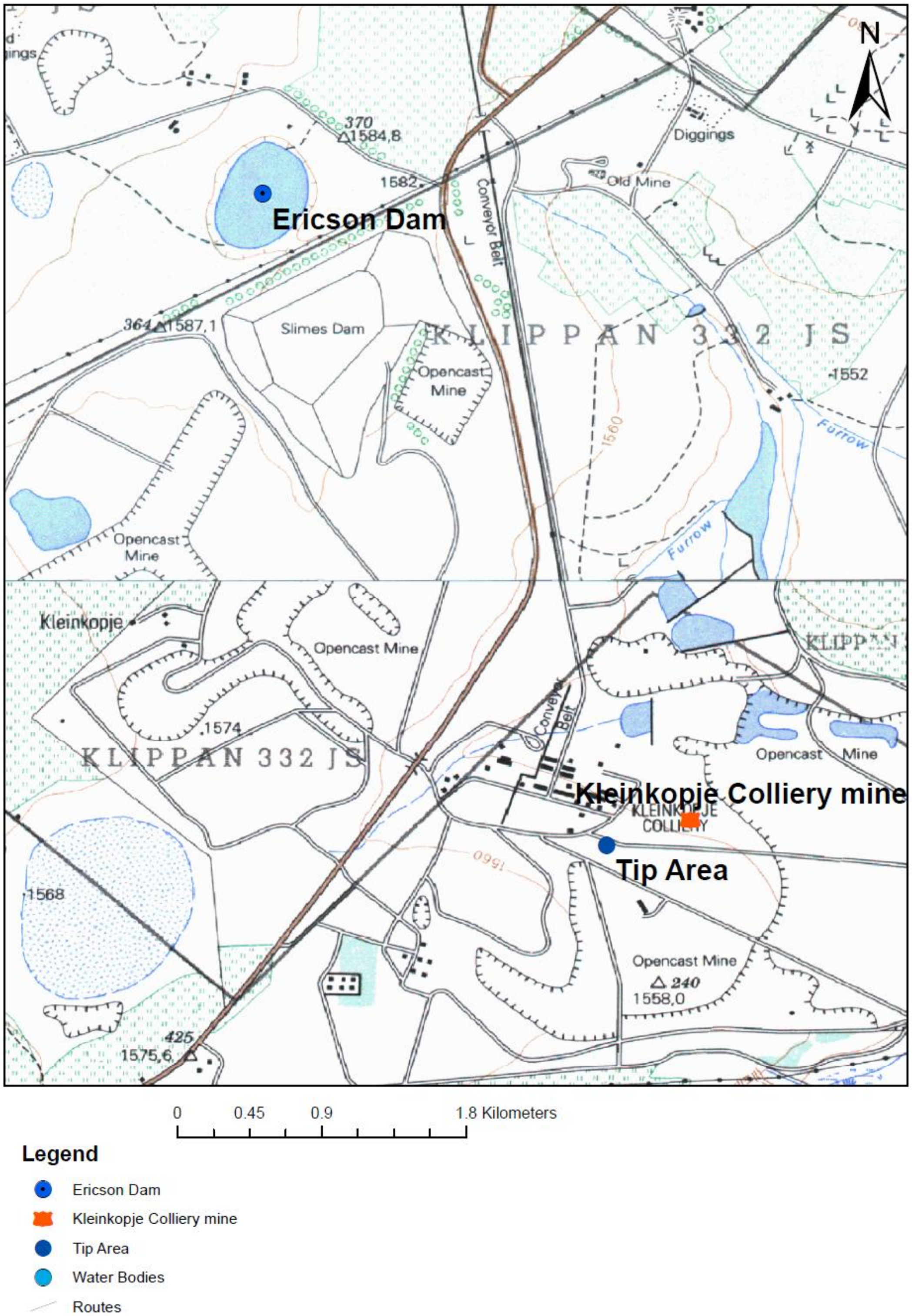


Figure 3.2: Sampling locations for Kleinkopje colliery mine near eMalahleni.

3.4 Sampling, data collection and analysis and procedures

The dust sampling procedure was based on the standard test method for collection and measurements of dust deposition (Settleable particulate matter) according to ASTM D1739:98 and ASTM D1739:82. The addition of water was done to the ASTM D1739:98 version dust buckets at the beginning of the sampling period. Copper sulphate was added to prevent the growth of algae. The buckets were intentionally made from UV-resistant PVC so as to avoid deterioration and to ensure the precise depth to height ratio. The samplers were located 10 meters away from each other with the bucket rims two meter above the ground.

3.4.1 Sampling instruments

a b

Figure 3.3: a) ASTM D1739:82 with bird ring or bird guard; b) ASTM D1739:98 with wind shield.

The bucket was placed on a stand that comprises a raised ring supported by four stabilizing bars above the base plate. This serves to prevent contamination of the sample by perching birds (figure 3.3).

“The directional dust deposit gauge according to BS 1747 part 5 has four vertical tubes enclosed at the top with a vertical slot in each tube facing the main four compass points” (N, S, E, W) (Parrett, 2008). The dust is collected in bottles located at the bottom of each of the collecting tubes. The gauge was exposed to the field for a period of 28 to 33 days. See figure 3.4 below.


Figure 3.4: Directional Dust Deposition Gauge.

Bottles were placed in the gauge and replaced monthly. The bottles were removed and labeled with locations and directions (N, S, E, and W). “The starting day for a measurement period was recorded. Any unusual event that may have occurred during the measurement period was recorded” (Parrett, 2008). Water was used to wash down the dust from the tubes into the collecting bottles. A soft brush was used to remove any dust which had adhered to the inside walls of the collecting tubes.

3.4.2 Sample collection procedures

The buckets and bottles were rinsed with distilled water to remove all the dust in the buckets. The sample buckets and dust sample bottles were labeled properly using a permanent ink marker. All necessary data and information, such as sample name, analysis date, mass of labeled sample and oven-drying date, were documented on the sample book and in an Excel spread sheet.

3.4.3 Analysis

The collected dust samples were analysed at the Environmental Geosciences Unit laboratory, Council for Geosciences. A filtration process was used to determine dust samples mass by separating dust and water and then drying the filter paper with dust on in an oven at 105˚C to dry for 24 hours.

3.4.3.1 Apparatus

- Bucher funnel; suction flask; filter paper 0.45um; distilled water; and spatula.
- Evaporation dishes, vacuum collector and drying oven to dry the samples.

3.4.3.2 Methods and procedures

- Filter papers were weighed by the use of an AXIS AD 500 scale to 0.0001 gram.
- One blank filter paper per batch was kept to determine paper mass changes due to the filtration and drying process.
- The funnel and evaporation flask were connected for filtration.
- 1000 ml of water was used for the simple non-directional buckets and 500 ml of water was used for the directional dust deposition gauge.
- A spatula was used to remove the dust in the buckets and the replacement bottle while filtering.
- Vacuum collector and pipe were used to drain water from the funnel so that the dust remained on the filter paper.
- Filter papers were put on evaporation dishes and placed into the oven at temperature of 105˚ C for 24 hours.
- The samples were cooled after drying in the oven.
- Dried filter papers were weighed to determine mass of dust collected.
- Deposition rate for vertical dust deposit gauge and horizontal dust flux were calculated using the below equation but differences in the cross sectional area: 1) for vertical dust deposit gauge the cross sectional area was measured

at the top part of the dust bucket; 2) for horizontal dust flux the cross sectional area was measured at the area of the slot of the directional dust flux).

Dust deposition rate equation:
D=W/A g/ (m^2-day)
Where:

D=deposition rate in grams/square meter/day, mg/ m^2-d
A=collection area, the cross sectional area as described above, m^2 and
W=mass collected, g.

3.5 Data analysis and interpretation tools/methods

The results were statistically analyzed to determine:
1) comparison between vertical deposit gauges for coal and gold mine,
2) correlation coefficient between ASTM D1739:98 (with wind shield) and ASTM D1739:82 (without wind shield). See table 3.2.

Table 3.2 Correlation between variables for gold mine and coal mine.

Correlation between variables	**Mines**
Comparison between three vertical deposit gauges ASTM D1739:98 (with wind shield) and ASTM D1739:82 (without wind shield) and ASTM D1739:98 (with water) and sum of horizontal dust flux	Gold mine and coal mine
Comparison between sum of horizontal dust flux and ASTM D1739:98 (with wind shield)	Gold mine and coal mine
Correlations between deposition values and local conditions	Gold mine and coal mine
Correlation between direction deposition results and direction of major dust sources	Gold mine and coal mine

The limit values proposed in South African National Standards 1929:2005 were used to interpret the results with reference to the acceptable dust deposition rates for various location types. Data obtained from the South African Weather Services were used to determine the wind direction for the eMalahleni area and the Driefontein area.

3.6 Statistical procedures

The dust deposition rates for coal and gold mines were analyzed separately. Variance analysis was performed using SAS procedures PROC GLM and BLOM. Date, location and gauge were used as explanatory variables (sources of variation) with mass as dependent variable (SAS Institute Inc, 2004). The GLM/ANOVA analysis assumes that the data are normally distributed but the raw dust measurements did not fit a normal distribution. The BLOM (Blom, 1958) option computes normal scores from the ranks of the raw data, so that the resulting variable is more normally distributed and therefore more suitable for analysis.

CHAPTER FOUR: RESULTS and DISCUSSIONS

4.1 Introduction

This chapter presents the analysis of results for the dust monitoring at an underground gold mine site on the Far West Rand and an open cast coal mine in the Eastern Highveld. Dust deposition rates for vertical dust deposition gauge and horizontal dust flux for a 14 month period (from September 2009 to October 2010) are presented. The results were analysed by using the Blom transformation and the General Linear Method (GLM) with Scheffe's and Bonferroni's tests. The comparison is between the dust deposition/flux rates measured with: 1) ASTM D1739: 1982 without wind shield; 2) ASTM D1739:1998 with wind shield; 3) ASTM D1739:1998 with water; 4) Directional Dust Deposition Gauge (BS 1747 part 5, directional dust deposition gauge). The limit values given in the SANS 1929:2005 standard were used to interpret the measured dust deposition rates.

Abbreviations for selected sites areas for ASTM D1739 and BS 1747 part 5 gauges for gold mine and coal mine

E: ED	East Ericson Dam
E: TA	East Tip Area
E: EVRC	East Village Recreational Club
E: LWH	East Leslie Williams Hospital
EDWOWSNW	Ericson Dam without wind shield and no water
EDWWSNW	Ericson Dam with wind shield and no water
EDWWSWW	Ericson Dam with wind shield and with water
EVRCWOWSNW	East Village Recreational Club without wind shield and no water
EVRCWWSNW	East Village Recreational Club with wind shield and no water
EVRCWWSWW	East Village Recreational Club with wind shield and with water
LWHWOWSNW	Leslie Williams Hospital without wind shield and no water
LWHWWSNW	Leslie Williams Hospital with wind shield and no water
LWHWWSWW	Leslie Williams Hospital with wind shield and with water
N: ED	North Ericson Dam
N: EVRC	North East Village Recreational Club
N: TA	North Tip Area

N: LWH	North Leslie Williams Hospital
S: ED	South Ericson Dam
S: EVRC	South East Village Recreational Club
S: TA	South Tip Area
S: LWH	South Leslie Williams Hospital
TAWOWSNW	Tip Area without wind shield and no water
TAWWSNW	Tip Area with wind shield and no water
TAWWSWW	Tip Area with wind shield and with water
W: ED	West Ericson Dam
W: TA	West Tip Area
W: EVRC	West East Village Recreational Club
W: LWH	West Leslie Williams Hospital

Abbreviations used in statistical tables:

DF	Degree of Freedom (Anselme, 2006)
TYPE III SS	Sum of squares (Anselme, 2006)
F value	Frequency value (Anselme, 2006)
GLM	General Linear Models
Pr>F	Probability > Frequency

4.2 Raw seasonal dust rates for vertical deposition gauge and horizontal dust flux

Table 4.1: Vertical and horizontal dust flux rates for summer; autumn, winter and spring (mg/m^2-d).

Description Label	9-Sep	9-Oct	9-Nov	9-Dec	10-Jan	10-Feb	10-Mar	10-Apr	10-May	10-Jun	10-Jul	10-Aug	10-Sep	10-Oct	Total
EDWWSNW	263	242	887	548	462	1861	2261	2000	207	546	553	459	388	457	**11134**
EDWOWSNW	146	227	816	1216	325	1209	648	346	209	274	470	231	259	264	**6637**
EDWWSWW	**332**	**338**	625	618	483	2333	1501	492	142	546	766	479	481	398	**9534**
S:ED	110	203	230	365	252	534	223	139	53	88	169	125	178	333	**3002**
N:ED	46	389	475	460	257	416	232	358	58	80	137	78	83	240	**3309**
W:ED	102	529	330	29	134	360	242	176	88	250	134	112	110	409	**3005**
E:ED	41	465	245	372	294	973	504	522	85	73	102	102	58	209	**4045**
Total	**299**	**1586**	**1280**	**1226**	**937**	**2283**	**1201**	**1198**	**284**	**491**	**542**	**417**	**429**	**1191**	**13364**
TAWWSNW	868	1001	1712	2996	1098	2131	1125	2666	1438	1718	2114	1444	2505	2144	**24960**
TAWOWSNW	764	531	944	961	377	729	857	940	579	555	792	820	746	764	**10359**
TAWWSWW	1403	1418	2098	3588	1259	2172	2277	2642	1640	2118	2518	1966	2375	2801	**32975**
S:TA	1254	710	1750	1120	409	1274	509	544	453	794	960	1112	1178	1181	**13248**
N:TA	379	421	465	414	2299	308	325	389	267	284	284	252	546	1575	**8108**
W:TA	1713	1995	642	2166	514	1250	247	911	696	1051	1399	384	1096	5681	**10745**
E:TA	725	522	571	3232	387	995	750	720	176	225	286	330	424	879	**10222**
Total	**2358**	**3648**	**3428**	**6932**	**3609**	**3827**	**1831**	**2564**	**1592**	**2354**	**2929**	**2078**	**3244**	**9316**	**49710**
EVRCWSNW	94	148	33	no data	no data	53	94	77	81	75	72	22	142	85	**976**
EVRCWOSNW	150	155	109	no data	no data	72	70	50	135	57	100	85	129	292	**1404**

Description Label	9-Sep	9-Oct	9-Nov	9-Dec	10-Jan	10-Feb	10-Mar	10-Apr	10-May	10-Jun	10-Jul	10-Aug	10-Sep	10-Oct	Total
EVRCWWSWW	98	96	140	no data	no data	75	88	92	48	83	51	70	101	325	**1267**
S:EVRC	12	58	53	no data	no data	230	88	102	17	78	3	17	56	105	**819**
N:EVRC	100	267	85	no data	no data	203	56	63	22	51	24	7	58	129	**1065**
W:EVRC	17	183	75	no data	no data	203	71	100	78	56	50	31	63	316	**1243**
E:EVRC	12	7	83	no data	no data	63	46	44	26	31	14	17	44	68	**455**
Total	**141**	**515**	**296**	**no data**	**no data**	**699**	**261**	**309**	**143**	**216**	**91**	**72**	**221**	**618**	**3582**
LWH:WWSNW	33	207	212	170	40	162	46	118	51	96	105	150	161	153	**1704**
LWH:WWOWSNW	51	251	96	66	87	18	81	66	62	90	237	192	288	279	**1864**
LWH:WWSWW	287	131	227	242	129	111	118	64	75	125	225	275	181	253	**2443**
S:LWH	46	100	156	198	139	63	93	73	2	39	31	46	78	61	**1145**
N:LWH	88	129	286	105	139	183	95	56	4	49	102	132	115	522	**2005**
W:LWH	29	137	144	137	51	117	80	14	17	80	53	31	198	164	**1252**
E:LWH	29	191	316	2245	125	43	68	24	17	34	49	95	56	100	**3392**
Total	**192**	**557**	**902**	**2685**	**454**	**320**	**336**	**248**	**40**	**202**	**235**	**304**	**335**	**847**	**7794**

Note 1: For vertical dust flux (dust deposition) the cross-sectional area of the bucket was used to calculate the specific deposition rate; for horizontal dust flux, the projected area of the vertical slot was used.

Note 2: A measurement or analytical error is suspected for the "East" value for Leslie Williams hospital (Dec 09) with 2245 mg/m^2-d.

Note 3: Colour code:

Below 600 mg/m^2-d - **Blue**

Over 600 mg/m^2-d - **Green**

Over 2400 mg/m^2-d – **Red**

Table 4.2: Classification in terms of the limits proposed by SANS 1929:2005 of the vertical deposition rates at the various locations.

Gold Mine: Seasons	Mine sites	Period	Target	Residential	Industrial	Alert
Summer	EVRC and LWH	Dec-Feb	√			
Autumn	EVRC and LWH	Mar-May	√			
Winter	EVRC and LWH	Jun-Aug	√			
Spring	EVRC and LWH	Sep-Nov	√	√		
Coal Mine: Seasons	**Mine sites**	**Period**	**Target**	**Residential**	**Industrial**	**Alert**
Summer	ED and TA	Dec-Feb				√
Autumn	ED and TA	Mar-May				√
Winter	ED and TA	Jun-Aug		√		
Spring	ED and TA	Sep-Nov	√	√		√

Note: Gold mine sites: EVRC East village recreational club and LWH Leslie Williams hospital; Coal mine sites: ED Ericson dam and TA Tip area.

4.3 Comparison between vertical deposit gauge for coal mine and gold mine

Results from coal and gold mines were analyzed separately. Analyses of variance were performed using the Blom transformation and SAS procedure PROC GLM (SAS Institute Inc, 2004). The Blom procedure is a ranking of data that is not normally distributed. The ranking is closer to normally distributed, allowing the use of GLM on the transformed data. Date and gauge type were used as explanatory variables (sources of variation) with collected mass as dependent variable.

4.3.1 Coal mine

The analysis of variance by variable for the "low dust" results is shown in table 4.3 below.

Table 4.3 Analysis of variance for coal low dust: Blom.

Source of variability	Degree of Freedom	Type II SS	Mean Square	Frequency Value	Probability >Frequency
Date	14	8.2332	6.3332	10.45	<0.0001
Gauge Type	4	1.5453	0.5151	8.5	0.0002

The variation caused by date was expected; this formed part of experimental design. The means for the gauge types were then tested by the methods of

Scheffe and Bonferroni. These methods are “single-step multiple comparison procedures which apply to the set of estimates of all possible contrast among the factor level means” (NIST/SEMATECH, 2003). As the horizontal and vertical gauges test for different variables, the focus in this section is on the difference between the Blom rankings of the vertical deposit gauge types.

Results of the Scheffe and Bonferroni tests (both giving the same results for the means) for the Blom rankings in the low deposition area in the coal mine are shown in table 4.4. In this representation of the results, similar letters in the third column indicate variables for which the means are not significantly different. As an example, the Blom means for the second and third rows do not differ significantly, indicating that the addition of water does not make a statistical difference. Similarly, the presence or absence of the wind shield where water is not added (second and fourth rows) is statistically significant.

Table 4.4: Scheffe test and Bonferroni test for coal low dust: Blom.

Row	Blom Means	Means difference indication	Number of Variables	Gauge Type
1	0.5328	A	14	Total Horizontal
2	0.3492	A	14	Wind Shield Without Water
3	0.3130	A,B	14	Wind Shield With Water
4	0.0665	B	14	Without Wind Shield Without Water

The analysis of variance by variable for the “coal high deposition” results is shown in table 4.5 below. In this representation, comparisons different at the 0.05 level are indicated by asterisks in the last column. The analysis indicates that the addition of water to a gauge with a wind shield does not yield significantly different Blom rankings (rows 5 and 8) whereas the wind shield makes a significant difference (rows 9 and 12).

Table 4.5: Scheffe test and Bonferroni test for coal high dust: Blom.

Row	Gauge type Comparisons	Difference Between Means	Simultaneous 95% Confidence Limits		
1	Total Horizontal -Wind + Water	0.4914	0.0902	0.8926	***
2	Total Horizontal -Wind Shield No Water	0.6898	0.2886	1.0910	***
3	Total Horizontal -No Wind Shield No Water	1.3011	0.8999	1.7023	***
4	Wind Shield + Water-Total Horizontal	-0.4914	-0.8926	-0.0902	***
5	Wind Shield With Water-Wind Shield No Water	0.1984	-0.1870	0.5839	
6	Wind Shield + Water-No Wind Shield No Water	0.8097	0.4243	1.1952	***
7	Wind Shield No Water-Total Horizontal	-0.0690	-1.0910	-0.2886	***
8	Wind Shield No Water-Wind Shield + Water	-0.1984	-0.5839	0.1870	
9	Wind Shield No Water-No Wind Shield No Water	0.6113	0.2259	0.9967	***
10	No windshield No Water - No Windshield + Water	-1.3011	-1.7023	-0.8999	***
11	No Wind Shield No Water-Wind Shield + Water	-0.8097	-1.1952	-0.4243	***
12	No Wind Shield No Water - Wind Shield +No Water	-0.6113	-0.9967	-0.2259	***

4.3.2 Gold mine

The analysis of variance by variable for the "low dust" results is shown in table 4.6 below.

Table 4.6: Analysis of variance for gold low dust: Blom.

Source of variability	Degree of Freedom	Type II SS	Mean Square	Frequency Value	Probability>Frequency
Date	11	5.5982	0.5089	2.6	0.0167
Gauge Type	3	5.7906	1.9302	9.86	<0.0001

Results of the Scheffe and Bonferroni tests (both giving the same results for the means) for the Blom rankings in the low deposition area in the gold mine are shown in table 4.7. The bottom three rows indicate no statistically significant difference for the use of water or for the use of a wind shield.

Table 4.7: Scheffe test and Bonferroni test for gold low dust: Blom.

Blom Means	Mean difference indication	Number of Variables	Gauge Type
-0.3094	A	12	Total Horizontal
-0.9129	B	12	Without Wind Shield Without Water
-1.0183	B	12	Wind Shield With Water
-1.2500	B	12	Wind Shield Without Water

The analysis of variance by variable for the "gold high deposition" results is shown in table 4.8 below. In this representation, comparisons different at the 0.05 level are indicated by asterisks in the last column. The analysis indicates that the only significant differences occur between the horizontal and vertical gauge types; neither the addition of water nor the presence of a wind shield results in significant differences.

Table 4.8: Scheffe test and Bonferroni test for gold high dust: Blom.

Gauge type Comparison	Difference Between Means	Simultaneous 95% Confidence		
Total Horizontal - Wind Shield + Water	0.3894	-0.1848	0.9636	
Total Horizontal -Wind Shield No Water	0.7620	0.1930	1.3414	***
Total Horizontal - No Wind Shield No Water	0.8152	0.2410	1.3894	***
Wind Shield + Water-Total Horizontal	-0.3894	-0.9636	0.1848	
Wind Shield + Water-Wind Shield No Water	0.3777	-0.1857	0.9412	
Wind Shield + Water-No Wind Shield No Water	0.4258	-0.1377	0.9892	
Wind Shield No Water-Total Horizontal	-0.7672	-1.3414	-0.1930	***
Wind Shield No Water-Wind Shield + Water	-0.3777	-0.9412	0.1857	
Wind Shield No Water-No Wind Shield No Water	0.0480	-0.5155	0.6115	
No Wind Shield No Water-Total Horizontal	-0.8152	-1.3894	-0.2410	***
No Wind Shield No Water-Wind Shield + Water	-0.4258	-0.9892	0.1377	
No Wind Shield No Water-Wind Shield No Water	-0.0480	-0.6115	0.5155	

4.4 Comparison between ASTM D1739:98 with wind shield, ASTM D1739:82 without wind shield (both case without water)

Comparison of the above analysis with the results obtained by Illenberger (2010) and Smith *et al*, (2010) leads to the conclusion (i) that the wind shield increases the mass of dust collected for a given location and (ii) that the percentage increase is higher for locations with a higher deposition rate. When starting a measurement programme it is however not possible to determine *a priori* what the rate will be. Also, for regulatory purposes, a single relationship independent of the absolute dust fall rate may be useful. In order to quantify the overall relationship between results from the two versions of ASTM D1739, linear correlation between all the result pairs was investigated.

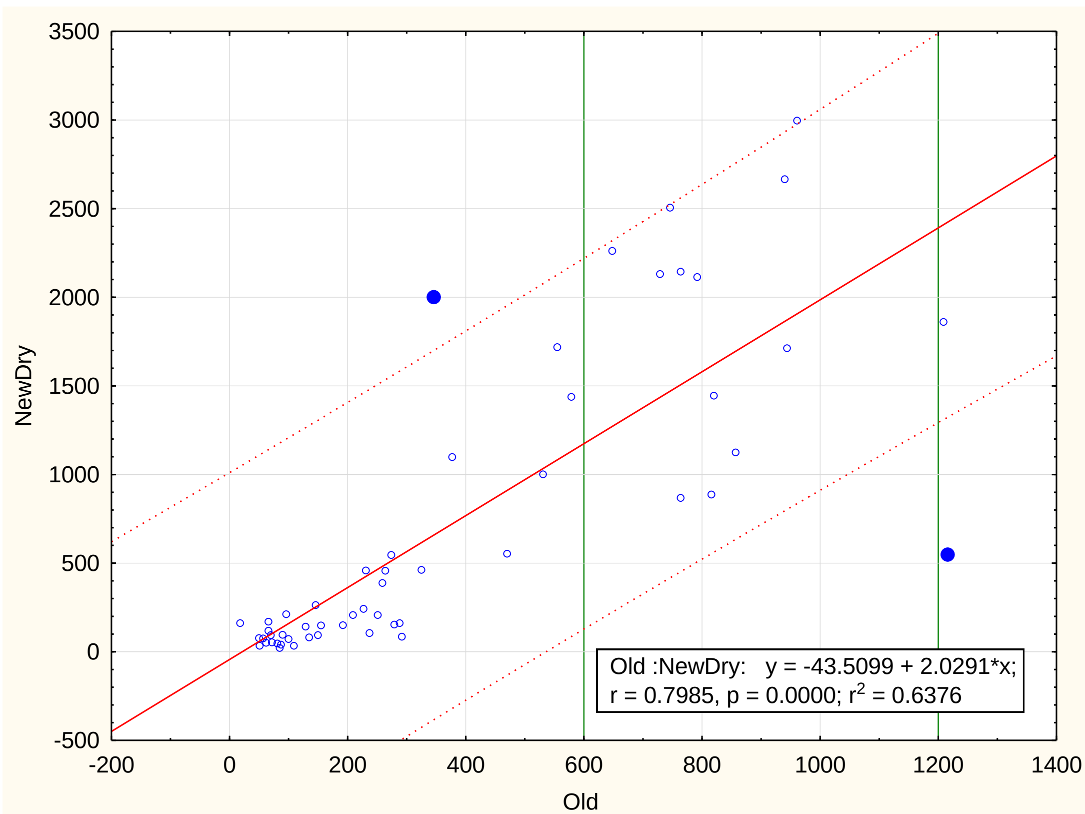


Figure 4.1: Comparison between all results for ASTM D1739:98 (with wind shield) and ASTM D1739:82 (without wind shield), (SAS Institute Inc, 2004).

After removing two obvious outlier values (indicated by solid circles), a reasonable correlation (R^2=0.6376 or 63.76%) is indicated between values obtained with and without the wind shield when both are used dry. It was shown earlier that the addition of water has a minor effect. Neglecting the small negative intercept (the value of which at -43.5 is small given the fairly high unexplained variability in results) (see figure 4.1 above), the average value obtained with the wind shield is 203% of that obtained without the wind shield. This has obvious implications for the limit values to be used for regulatory purposes.

4.5 Correlation between vertical dust deposition and horizontal dust flux values

In order to quantify the ratio between vertical and horizontal dust flux, the correlation between result pairs obtained by ASTM D1739:98 (dry) and the dust collected by the BS 1747 part 5 gauge in all wind directions (i.e. total horizontal flux) was investigated.

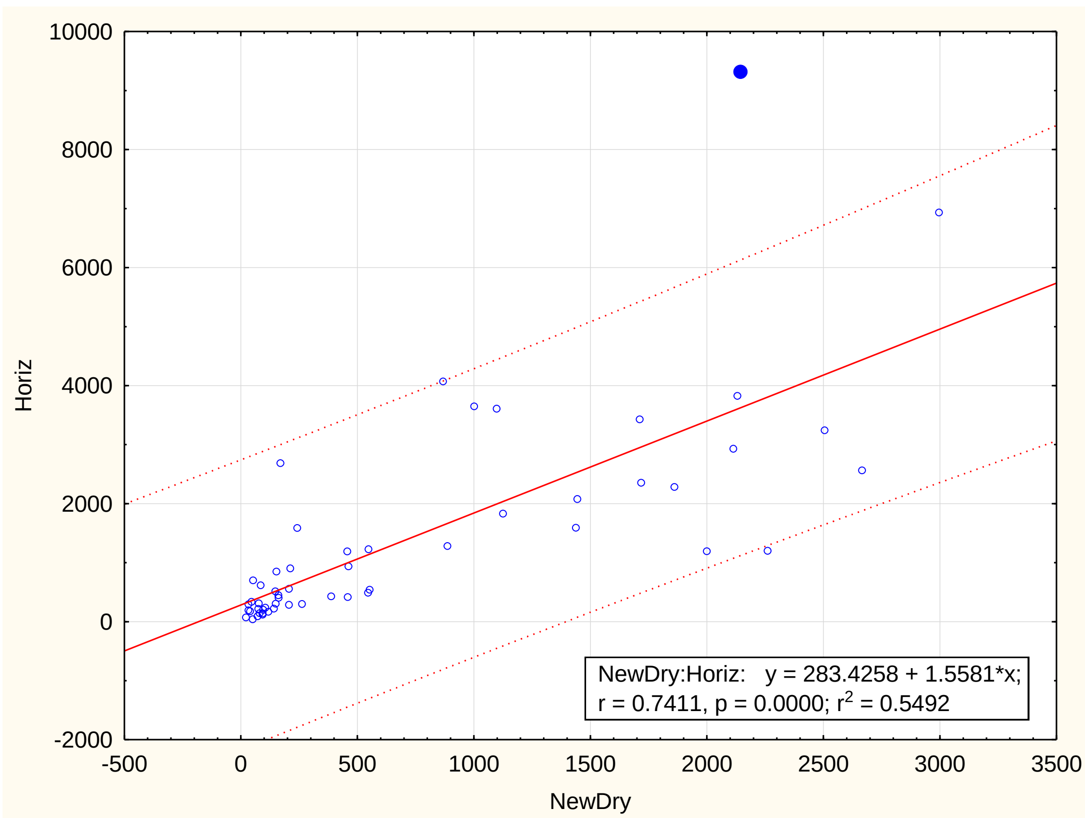


Figure 4.2: Comparison between the sum of horizontal dust flux and ASTM D1739:98 for gold mine and coal mine.

After removing one obvious outlier (indicated by the solid data point), the correlation coefficient between the sum of horizontal dust fluxes and the vertical deposition obtained with the wind shield included is somewhat less than that obtained between “old” and “new” vertical deposition gauges. The correlation is positive, indicating the possibility of using the BS 1747 part 5 horizontal dust flux gauge on its own as a tool for assessing dust nuisance.

4.6 Correlation between deposition values and local conditions

4.6.1 Meteorological results for eMalahleni area and Driefontein area

Meteorological results provide values for wind speed, wind direction and atmospheric stability, which affect what the dust concentration is (or has been) at a particular location. Meteorological conditions are the most important parameter which influences dispersion and deposition of fugitive dust (Colls, 2002). The traditional wind rose indicates the frequency of directions from which the wind is blowing as well as the wind speed for each direction. Figures 4.3 to 4.5 below were obtained from the South African Weather Services for the eMalahleni region (South African Air Quality Information System, 2010).

In summer, wind in the eMalahleni region blows predominately from east sector with wind speed from 5-10 ms^{-1}. During winter, wind in eMalahleni is still predominantly from the east sector and east-southeast, but with a reduced average wind speed. Autumn wind blows from the east sector with wind speed from 3-4 ms^{-1}. There is a prominent signal from the north, especially during spring.

The annual average wind direction in eMalahleni is from the eastern sector and east-south eastern sector with a maximum wind speed of 20 ms^{-1}. The day time wind direction is predominantly from the north-western sector with the highest wind speed in excess of 20 ms^{-1}. Night time wind direction is predominantly from the east-south-eastern sector with a maximum wind speed of 20 ms^{-1}.

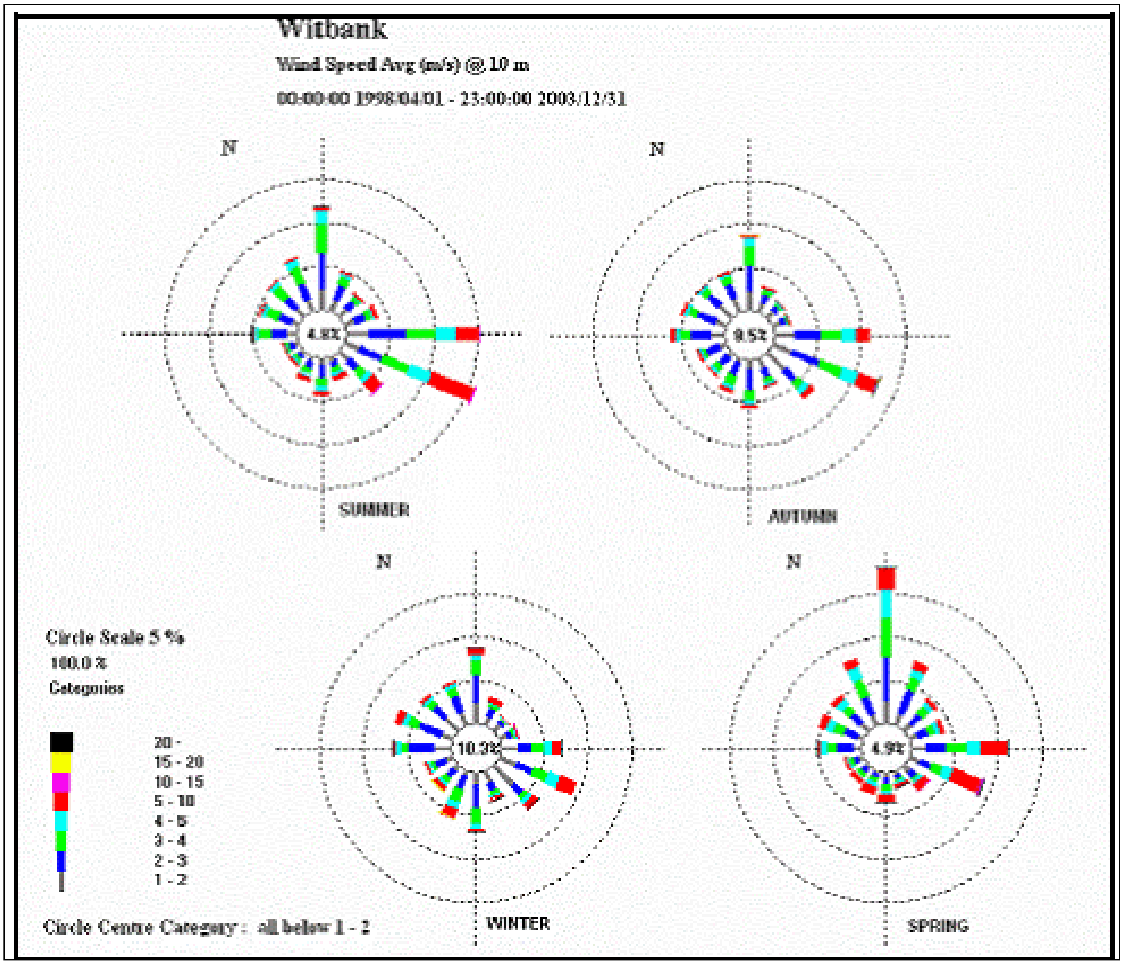


Figure 4.3: Seasonal wind roses from 01 April 1998 to 31 December 2003 monitoring period for eMalahleni area.

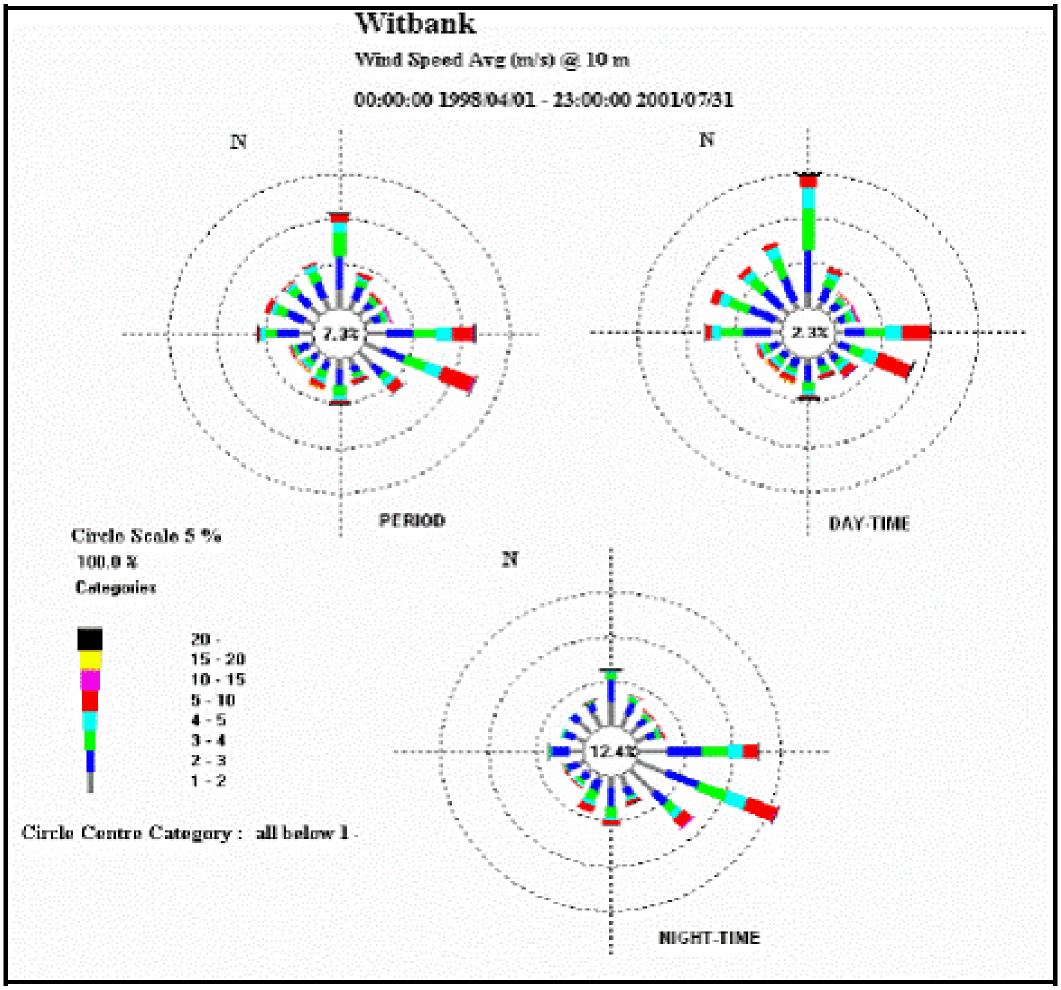


Figure 4.4: Diurnal variation in wind direction from 01 April 1998 to 31 December 2001 monitoring period for eMalahleni area.

Over a period of twelve months, the wind in the Driefontein area is mainly from the north-western sector, but with major contributions from the north-eastern sector. This is shown in figures 4.5 and 4.6 below. Maximum wind speed is from 5-10 ms^{-1}. During day time wind blows from the west sector and during night–time it blows predominantly from the north sector.

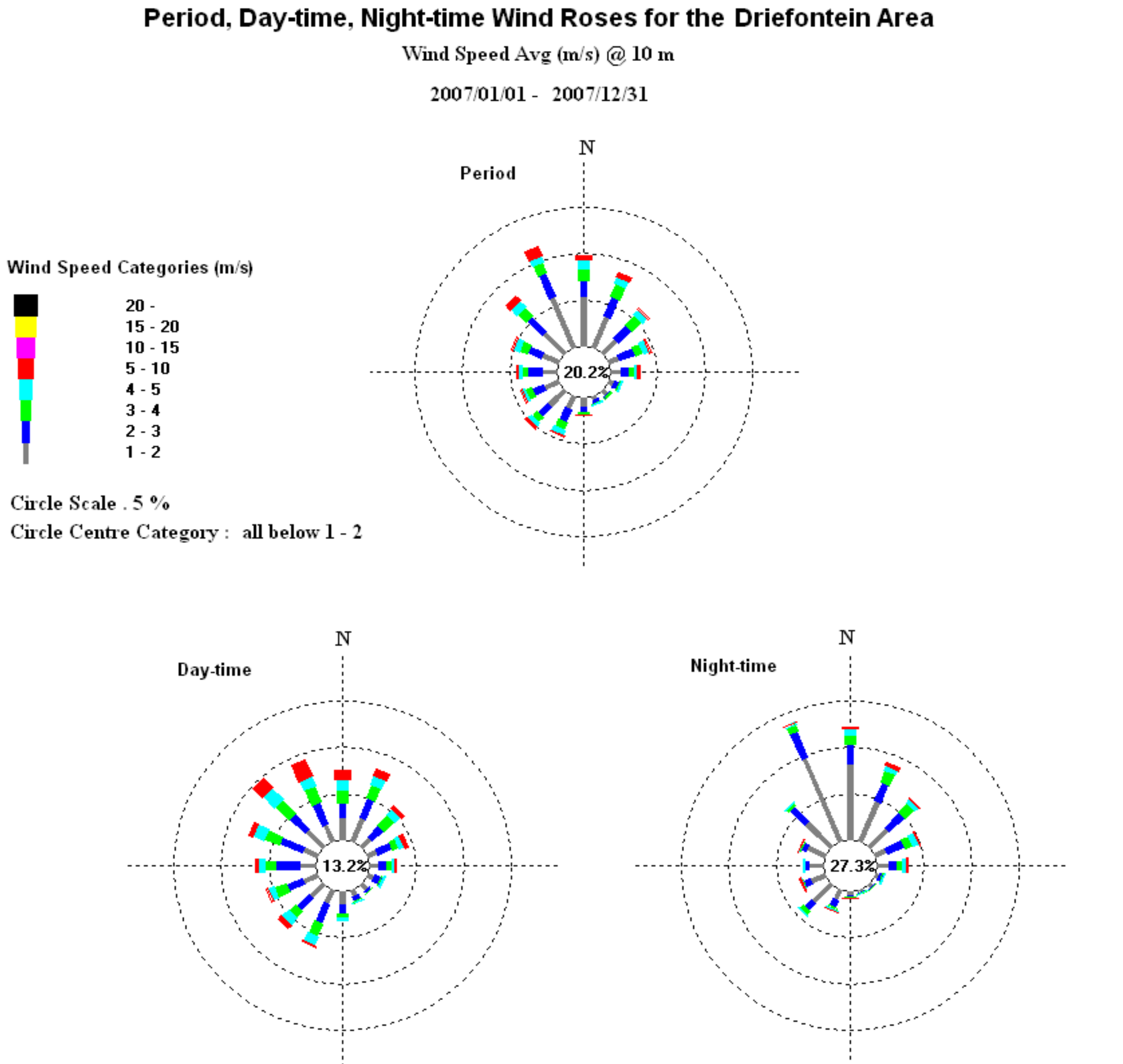


Figure 4.5: Diurnal variation in wind direction from 01 January 2007 to 31 December 2007 monitoring period for the Driefontein area.

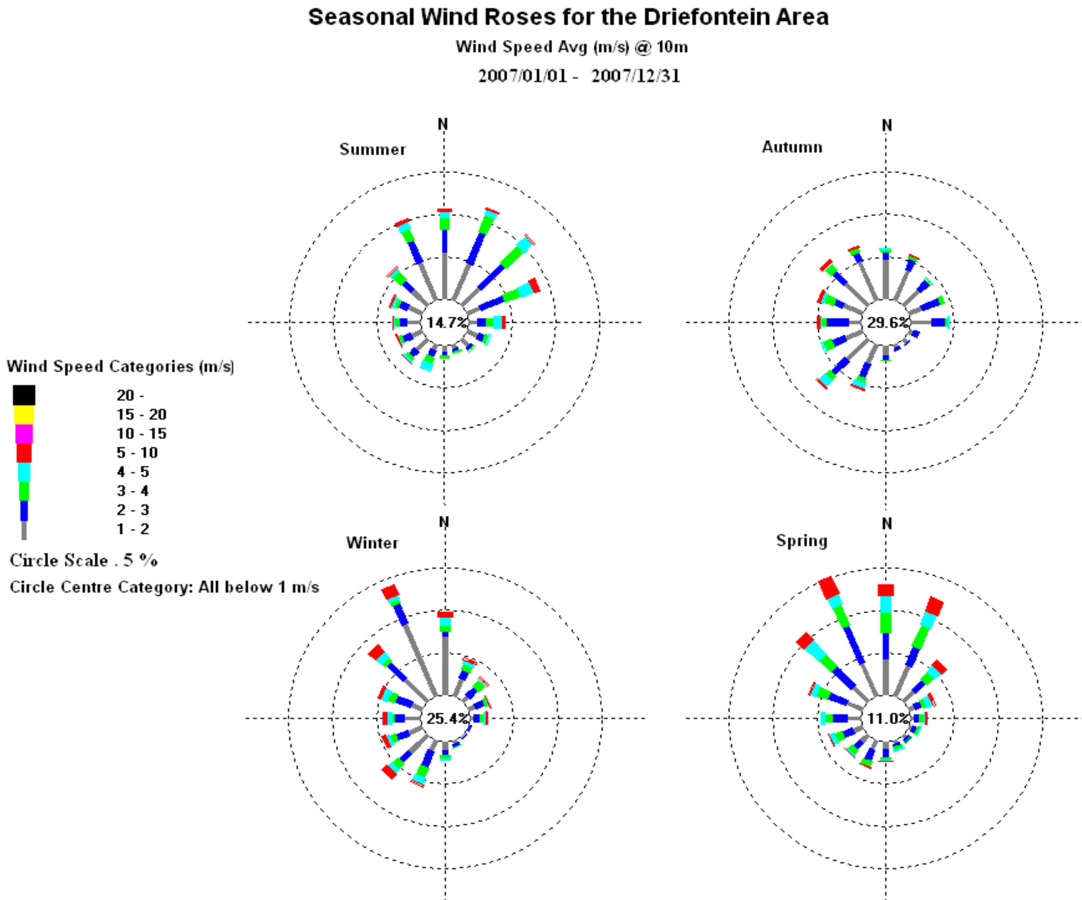


Figure 4.6: Seasonal wind rose from 01 January 2007 to 31 December 2007 monitoring period based on wind field data for Driefontein area.

In summer, wind in the Driefontein area is predominately from the north-east sector with maximum wind speeds from 5-10 ms^{-1}. During autumn the south-western component is stronger. During winter, wind from the north-west is predominant. This trend continues during spring while in summer the north-east component increases in frequency.

4.6.2 Correlation between deposition results and direction of major sources

4.6.2.1 Coal mine results

Results for the two coal mine test areas are given in figures 4.7 and 4.8 below.

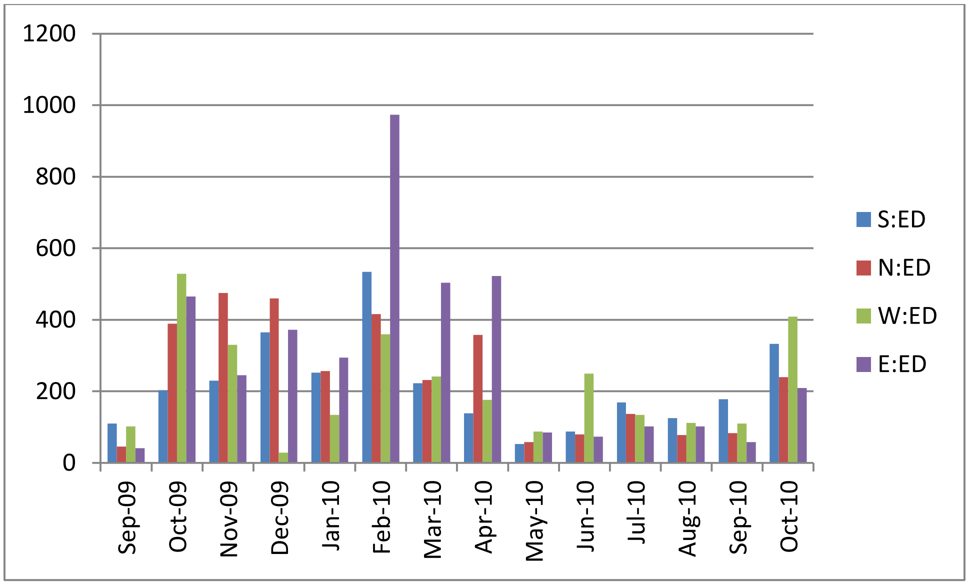


Figure 4.7 Horizontal dust flux dust rates per month for Ericson dam for coal mine.

The highest monthly average dust deposition rate was recorded in February 2010 with 973 mg/m^2-d. The monthly average dust deposition rates for October 2009, February 2010, March 2010 and April 2010 were somewhat higher than the annual average. Although Ericson dam was in the area with supposedly "low" deposition values, a very high value was recorded from the east in February 2010. This corresponds with the high values found in the corresponding month for vertical deposition. The lowest dust horizontal flux rate was from the west in December 2009 with 102 mg/m^2-d. This indicates that there were few dust generating activities from this direction. The result shows that the source of direction was mainly from the east.

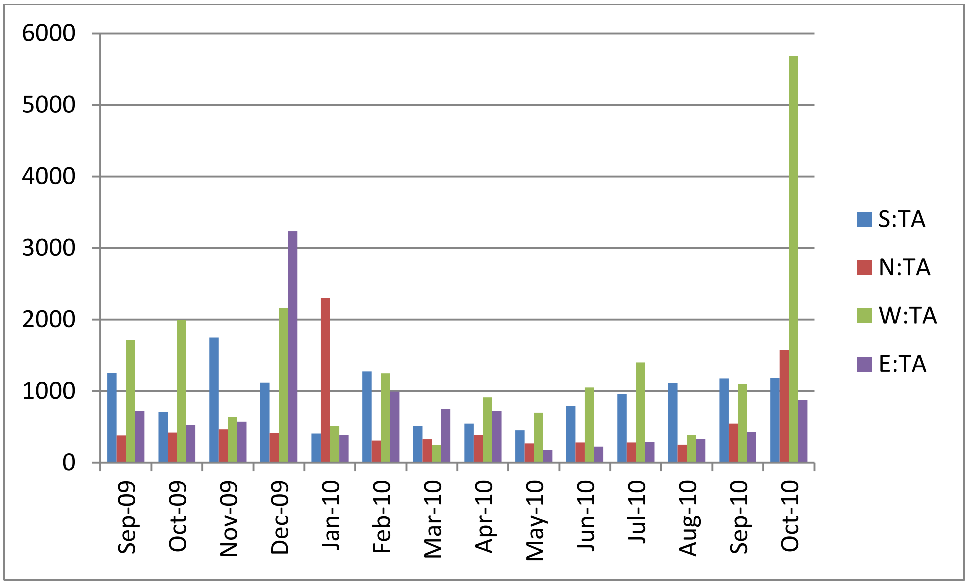


Figure 4.8 Horizontal dust flux dust rates per month for Tip area for coal mine.

The monthly flux observed at Tip area for the coal mine indicated that the dust deposition rate was the highest with 5681 mg/m^2-d during October 2010 probably due to higher than average wind speeds in spring; the lowest was in May 2010. There are unpaved roads next to Tip area and the mine trucks driving from the mine contributed to the dust deposition rates generated. Mine trucks driving through Tip area require constant dust suppression on the roads in the area. Dust suppression using water was carried out regularly on mining roads.

4.6.2.2 Gold mine results

Results for the two rest locations at the gold mine are given in figures 4.9 and 4.10 below.

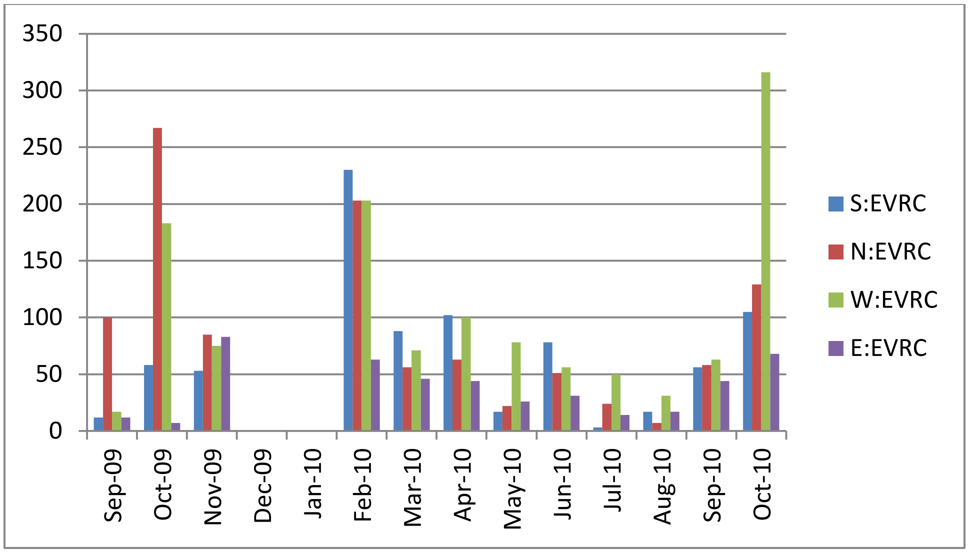


Figure 4.9: Horizontal dust flux dust rates per month for East village recreational club for gold mine.

Monthly average flux rates show that in October 2010 the dust deposition was recorded as the highest with 316 mg/m^2-d. The direction of the source was from the west. December 2009 and January 2010 both recorded no data because the dust monitoring equipment was destroyed and had to be reinstalled in January 2010.

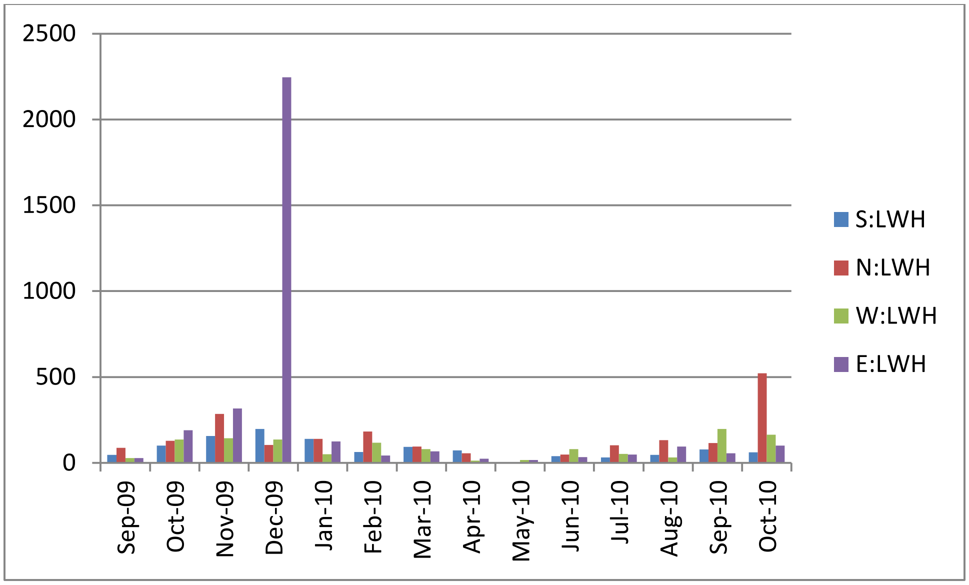


Figure 4.10 Horizontal dust flux dust rates per month for Leslie Williams hospital for gold mine.

The monthly dust flux for December 2009 was the highest with 2245 mg/m^2-d from the east. No obvious reason for this anomaly presents itself; possibly a single major materials movement even occurred at Driefontein mine east of the hospital.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

- Overall, there is a significant statistical relationship between the results obtained with ASTM D1739:98 with wind shield and ASTM D1739:82 without wind shield.
- The correlation coefficients between ASTM D1739:98 and ASTM D1739:82 are given as 0.88 and 0.94 by Smith *et al* (2010) for opencast coal and surface gold recovery respectively, although the present study did not show a statistically significant correlation for the underground gold mine and an overall correlation coefficient of 0.64 for the combined results
- There is evidence that the intent of the introduction of the wind shield improve the capturing of the dust into the dust bucket.
- The comparison of the old version (without wind shield) and new version (with wind shield) in this study shows an average increase in the measured flux rate of 103% (see figure 4.1) when the wind shield is used with dry buckets. This increase is comparable to those for similar studies reported by Illenberger (2010) and Smith *et al* (2010)
- Generally, the results for gold mines indicate that dust deposition rates were lower than for the opencast coal mines.
- There was no statistically significant difference in collection efficiency between ASTM D1739:98 (wet) and ASTM D1739:98 (dry). In view of the high variability of the method, the addition of water is therefore not considered necessary and its omission will reduce the necessity for inspection between bucket changes in areas of high net evaporation rates, thus reducing operational costs.
- The directional dust deposition gauges can be used to determine the direction of the dust source relative to the dust monitoring location.
- There is a reasonable correlation (correlation coefficient of 0.55) between vertical dust flux as measured by ASTM D1739:98 and total horizontal dust flux as measured by BS 1747 part 5.
- BS 1747 part 5 could potentially be used on its own as an indicator of nuisance caused by coarse dust, but for the method to be used as a legal instrument, the setting of its limit values would be required.

5.2 Recommendations

- It is recommended that the South African mining sectors should conduct dust monitoring using the latest version of ASTM 1739:98 to determine the dust deposition rate.
- The benefits of using ASTM 1739:98 are that it is the most cost efficient internationally accepted method to monitor dust deposition.
- The BS 1747 part 5 directional dust deposition gauge could be used to determine the direction of the dust source, but additional work to determine acceptable limit values would have to be done.

CHAPTER SIX: REFERENCES

American Geological Institute (1998) National Geoscience Data Repository System Phase II; final report ,30 January 1995 to 28 January 1997,performed under grant No.DE-FG 22-95BC 14833,submitted to the office of Fossil Energy, U.S. Department of Energy,199.

Anglo Coalfields, (2011)“Anglo Coalfields Annual Report”, URL:http://www.anglocoalfields.com/…/annual report 2011 [20 January 2011].

Anselme, K and Bigerelle, M (2006) “Statistical demonstration of the relative effects of surface chemistry and roughness on human osteoblast short-term adhesion”, *Journal of Material Science Materials in Medicine,* 17(5), 471-479.

ASTM International (1982) D1739-70 (Re-approved 1982): Standard Test Method for Collection and Measurement of Dustfall (Settleable Particulate Matter); West Conshohocken, Pennsylvania, PA, DOI: 10.1520/D1739-98R10.

ASTM International (2010) D 1739-98 (Re-approved 2010): Standard Test Method for Collection and Measurement of Dustfall (Settleable Particulate Matter); West Conshohocken, Pennsylvania, PA.

Barnard, D, Friend, F and Visser, H (2006) *Road map to Environmental Legislation* 3rd edition, ISBN 0620376732.

Blanco-Canqui, H and Lal, R (2008) *Principles of Soil Conservation and Management*, Springer, New York

Blom, G (1958) *Statistical Estimates and Transformed Beta Variables*, New York: John Wiley & Sons, Inc.

British Standards Institute, (1972) BSI 1747 Methods for the measurement of air pollution Part 5, Directional dust gauges.

Bullard, JE, Livingstone, I, Parsons, AJ and Abrahams, AD (2009) “*Dust”* 2nd edition, Netherlands, Springer.

Coal for Africa Limited, (2014), URL: http:www.coalofafrica.com [2014 January 20].

Colls, J (2002) *Air Pollution* 2nd edition, New York; Taylor & Francis.

Combes, RS and Warren, DA (2005) "Characterising and controlling industrial dust: a case study in small particle measurement", *Environmental Monitoring and Assessment*, 106(1-3), 43-58.

Dämmgen, U, Erisman, JW, Cape, JN, Grünhage, L and Folwer, D (2005) "Practical considerations for addressing uncertainties in monitoring bulk deposition", *Environmental Pollution*, 134(3), 535-548.

Datson, H and Birch, WJ (2007) "The development of a novel method for directional dust monitoring", *Environmental Monitoring and Assessment,* 12 (12), 301-308.

Dombrowski, N, Foumeny, DB, Ingham, YD and Qi, YD (1996) "Collection efficiencies of gauges at varying wind and pitch angles", *Atmospheric Environment*, 30(22), 3777-3788.

Doyle, B (2012), Australian Network of Environmental Defenders Officers Inc, URL: http://www.edo.org.au [2014 January 17].

Du Droit, (2010) "Airborne Dust Monitoring Equipment" Pacwill Environmental: Dust Gauge URL: http://www.pacwill.ca/Hanby/iso_dust_gauge.html [2011 December 16].

Environment Agency, (2003) "Monitoring of particulate matter in ambient air around waste facilities", Technical Guidance Document Monitoring M17, *Environment Agency*, London.

Free Dictionary, (2005), URL: http:www.thefreedictionary.com [2014 January 20].

Fryrear, DW (1986) "A field dust sampler", *Journal Soil and Water Conservation,* 41, 117-120.

Fuglsang, K (2002) "An automatic sampler for measurement of dust-deposition rates around fugitive sources", *Journal Air and Waste Management Association,* 52 (7), 789-795.

Galbraith, JH and Hingston, FJ (1991) Application of a directional dust gauge to measurement of impaction at atmospheric salt, *Atmospheric Environment Part A*, 25(10), 2211-2222.

Ganor, E (1975) "*Atmospheric dust in Israel, sedimentological and meteorological analysis of dust deposition*", PhD Thesis, Hebrew University of Jerusalem.

Goldfields, (2007) "*Goldfields Annual Report",*
URL: http://www.goldfields.co.za/cd_ar_2007.php [2010 March 31].

Goldfields, (2008)"*Goldfields Annual Report*",URL:http://www.goldfields.co.za/pdf/sustainability_reports/sustainability_report_2008.pdf[2010 March 31].

Goossens, D (2001) "Wind tunnel and field calibration of five aeolian sand traps", *Geomorphology*, 35(3), 233-252.

Goossens, D and Offer, ZY (2000) "Wind tunnel and field calibration of six aeolian dust samples", *Atmospheric Environment,* 34(7), 1043-1057.

Grünhage, L, Dämmgen, U, Kuster, A and Jäger, HJ (1993) "Response of grassland ecosystem to air pollutants: Experimental concept and site of the Braunschweig Grassland Investigation Program", *Atmospheric Environment Pollution,* 1(2), 163-171.

Hall, DJ (1994) "Designs for a deposition gauge and a flux gauge for monitoring ambient dust", *Atmospheric Environment*, 28(18), 2963-2979.

Hall, DJ and Upton, SL (1988) "A wind tunnel of the particle collection efficiency of an inverted frisbee used as a dust collector", *Atmospheric Environment*, 22(7), 1383-1394.

Hall, DJ, Upton, SL and Marsland, GW (1993) "Improvements in dust gauge design", In: Couling, S. (Ed), *Measurements of Airborne Pollutants*, London: Butterworth Heinemann.

Hamilton, J.D (1994) *Time Series Analysis*, Princeton University Press, ISBN 0-691-0489-6.

Hinds, WC (1982) *Aerosol Technology: Properties, Behavior and Measurement of Airborne Particles*, New York: John Wiley and Sons

Illenberger, W (2010) "Comparisons between ASTM 1739-82 and ASTM 1739-98 for Coast and Inland sites", Personal communication.

Implex Limited, (2012) URL: http://www.implex.co.za [2014 January 18].

International Aluminium Institute (2012), Mining case studies, URL:http://www.bauxite.world-aluminium.org/mining/casestudies/weipa.html[2014 January 19]

Janssen, W and Tetzla, G (1991) "Entwicklung und Eichung einer registriereden Suspensionsfalle", *Zeitschriff fur Kulturtechnik und Landensentwicklung* 32,167-180.

Jia, Q (2008) "*Coarse dust around mining areas - A study of available dust collectors and their efficiency*", MSc Thesis, Department of Civil and Environmental Engineering, Lulea University of Technology.

Kohler, A and Fleck, W (1966) "Vergleichende Staubniederschlags-und Staub-konzentrations messungen, *Staub Reinhalting der Luft"*, 26 (3), 105 - 110.

Kuhn, G (2011) "Environmental and Hygiene Engineering", URL:http://www.dust-monitoring-equipment.com/fallout/dustwatch.html. [2013 May 15].

Lodge, JP (1988) *Methods of Air Sampling and Analysis,* Boca Raton: Lewis Publishers, 3rd ed.7, 37-42,313-314,389-393.

Lottermoser, BG (2003) *Introduction to mine waste,* 2nd ed, London: Springer.

Mace Technologies (2008) DUSTDESC sales brochure. http://www.macetech.co.za/DUSTDESC1.htm, [2014 January 9].

Maeda, Y, Moroka, J,Tsujino, Y, Satoh, Y, Zang, X, Mizoguchi, T and Hatakeyama, S (2001) "Material damage caused by acidic air pollution in east Asia", *Water, Air and Soil Pollution*, 130 (1-4), 141-150.

New Zealand Ministry for the Environment, (2000) *Health Effects of Eleven Hazardous Air Contaminants and Recommended Evaluation Criteria,* Air Quality Technical Report 13, Wellington.

New Zealand Ministry for the Environment, (2002) *Ambient Air Quality Guidelines 2002 update* Air Quality Technical Report 32, Wellington.

Nilu Norwegian Institute for Air Research, (2010) URL:http://www.nilu.no/products [2011 May 13].

NIST/SEMATECH (2003): e-Handbook of Statistical Methods. http://www.itl.nist.gov/div898/handbook/ [2014 January 9].

OSHA, (2008) Dust Control Systems, URL:http://www.osha.gov.SLCT [2014 January 19].

Pacwill Environmental Ltd, (2008) URL:http://www.pacwill.ca [2014 January 18].

Parker, JD, Schoendorf, KC and Kiely, JL (1994) "Associations between measures of socio-economic status and low birth weight, small for gestational age, and premature delivery in the United States", *Ann. Epidemiol*, 4, 271–278.

Parrett, FW (2008) "Directional Dust Deposit Gauge to B.S.1747", Parrett Limited Technical Development: Dust Deposition Measurements URL:http://www.parrett.uk.com [2010 March 14].

Peterson, TC, Karl, TR, Kossin, JP, Kunkel, JH, Rimore, L, McMahon, JR, Vose, RS and Yi, X (2013) "Changes in weather and climate extreme: State of knowledge relevant to air and water quality in the United States", J *Air &Waste Management Association*, 64(2), 184-197.

Ralph, MO and Barrett, CF (1984) *A Wind-tunnel Study of the Efficiency of Three Deposit Gauges*, Stevenage: Warren Spring Laboratory, Report No: LR499 (AP), Oct l984.

Ralph, MO and Hall, DJ (1989) "Performance of the British Standard Directional Dust Gauge", paper no: W89001 (PA), Warren Spring Laboratory, UK.

SANS 1929:2005 "South African National Standard - Ambient Air Quality - Limits for common pollutants" *Pretoria:* South African Bureau of Standards, 13-14.

Schwela, D (1998) "Health and Air Pollution-A Developing Country's Perspective",Paper1 A-1, *Paper of the 11th World Clean Air and Environmental Congress*, 13-18 September 1998, Durban, South Africa.

Smith, J, Myles, CJ and Annegarn, HJ (2010) "Comparison of dust fall out rates using old and new ASTM D 1739 methods for dust deposition sampling", *Paper presented at Annual National Association for Clean Air Conference*, 13-15 October 2010, Polokwane.

Sow, M, Goossens, D and Rajot, JL (2006) "Calibration of the MDCO dust collector and of four versions of the inverted frisbee dust deposition sampler", *Geomorphology,* 82(3-4), 360-375*.*

Standards Australia Limited, (2010) "What is a Standard?"
URL: http://www.standards.org.au/DevelopmentStandards/aspx [17 August 2013].

State of Air Report 2009 *A report on the state of the in South Africa,* Department Environmental Affairs, URL:http://www.environment.gov.za [2010 November 16].

Statistical Analysis Systems (SAS) Institute Inc, (2004) "SAS/STAT User's guide, Version 9.1". Cary, NC: SAS Institute Inc.

Statistics Department South Africa, 2008) http://www.statssa.gov.za/...p03011/2008.pdf.

Statistics Department South Africa, 2007)http://www.statssa.gov.za/…p03011/2007.pdf.

Swaminathan, S, Lu H, Willliams RW, Lu L and Jablonski, MM (2013) "Genetic modulation of the iris transillumination defect: a systems genetics analysis using the expanded family of BXD glaucoma strains", *Pigment Cell & Melanoma Research,* 26(4), 487-498.

Tamenti, T (2007) "Feasibility study of replacing bottom dump trucks with rear dump trucks at Kleinkopje Colliery", *Southern African Institute of Mining and Metallurgy*,107,265-279.

Tsay, R.S (2005) *Analysis of Financial Time Series*, John Wiley & Sons, New York

UCL, (1999) Department of Geography, United Kingdom, URL:http:wwww2.geo.ucl.ac.uk [2014 January 18].

Vallack, HW (1995) "A field evaluation of frisbee-type dust deposit gauges", *Atmospheric Environment,* 29(12), 1465-1469.

Vallack, HW and Shillito, DE (1995) "Suggested guidelines for deposited ambient dust", *Atmospheric Environment*, 32(16), 2737-2744.

Walton, G (2001) *"Low Cost, Directional Monitoring of Nuisance Dust around Mineral Workings*", Report of Mineral Industry Sustainable Technology Project for MIRO, Leeds, UK.

White, HV (2003) "South Africa Witwatersrand Gold Play Targets Mega-Million-Ounce Jackpot in a Potentially New Exploration District" Wits Basin Precious Minerals Inc",URL:http://www.witsbasin.com/reports/Bull&Bear-witsbasin-1203.pdf [23 December 2012].

Wilson, SJ and Cooke, RU (1980) "Wind Erosion", In: Kirkby, M.J, Morgan, R.P.C (Eds), *Soil Erosion*, Chichester: Wiley 217 -251.

Zunckel, M, Naiker, Y and Raghunandan, A (2010) "*Air Quality Baseline Assessment for the Highveld Priority Area (Draft)",* Report to Department of Environmental Affairs" UMoya-NILU Consulting (Pty) Ltd, Pretoria.