Characterising South Africa's Major Dust Sources

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DECLARATION

‘I know the meaning of plagiarism and declare that all of the work in the dissertation (or thesis), save for that which is properly acknowledged, is my own’.

Sisanda Ongeziwe Bekiswa

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ABSTRACT

The study investigates the surface controls of major dust emissions and determines the spatial distribution of major dust source in South Africa. This study follows a multi-disciplinary approach where primary and secondary data were used. The main objective of the study is to determine the spatial distribution of South Africa's Major Dust Sources. Meteosat Second Generation (MSG) satellite imagery, land use and land cover maps were used to achieve the first and the second objectives of the study. Primary data involved sampling 30 soil samples in the field in order to achieve the third objective of the study. The crust, soil moisture, soil texture and grain size are all controls of dust emission. This investigation is however focused predominantly on grain size characteristics. GIS methods were also used to determine soil type from the African soil map. Soil samples in both provinces were then collected to assess the Particle Size Distribution (PSD) of the soils. The particle size was determined based on a sieve analysis for grain sizes that were greater than 2mm and laser diffractometry, MasterSizer (Malvern) was used to achieve this. The results from the Malvern were later put to R Statistics where they were clustered into eight clusters to determine similarities and difference of the grain size. Because there is no uniqueness in the soil types found in the study area, there were no solid conclusions made based in them. The results show that the soil types are found across South Africa but not the same amount of dust activity was detected in the other parts of the country. Previous studies show that global significant dust sources are natural sources such as lakes, pans and depressions. However, results demonstrate that South African dust sources are anthropogenic sources resulting from commercial agriculture in semi-arid regions. This study has demonstrated that surface sediments suitable for dust production are a mixture of fine material, silt (50µm) and coarse material, sand (2000µm) and it appears that all clusters in this study all contained both mixtures and all have potential to emit dust.

Keywords; Particle Size Distribution, GIS, Gradistats, Dust Events

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1. GENERAL INTRODUCTION

1.1. Dust and Dust Sources: Global Context

Understanding the properties and controls of Earth's major dust sources is important because of the widespread effects on the terrestrial, biological and atmospheric processes Tegen and Lacis, 1996) including the global radiation balance (Tanaka & Chiba, 2006). The diverse chemical and physical composition of particles determines varied scattering and absorption of solar radiation (Tanaka & Chiba, 2006). This results in uncertainties when it comes to understanding current and future climate controls. Dust is mainly produced by Aeolian erosion from bare and unprotected surfaces in arid and semi-arid areas. Numerous studies show that most of the global dust load is emitted from continental deserts (Pierre *et al.,* 2012) their inland basins as well as disturbed surfaces (Tanaka & Chiba, 2006). For example about 40 million tons of dust is transported annually from the Sahara (Washington *et al.,* 2009 and Koren *et al.,* 2006). It is proposed to be the main mineral aerosol source that fertilizes the Amazon basin, generating a dependence of the health and productivity of the rain forest on dust supply from the Sahara.

Bullard *et al.* (2011) states that the distribution of dust varies through space and time. The presence and supply of fine material is variable depending on the environmental production and storage of dust sized grains. These are not always released to the atmosphere depending on dynamic surface conditions which may inhibit availability even if there is enough wind for transport. The presence of atmospheric dust is therefore controlled by supply limitations, availability limitations and transport limitations. The first two of which are largely governed by the source area and surface characteristics. The source will hold the fine material and given the right conditions release dust to the atmosphere. The controls and emission of dust is predominantly related to a range of characteristics as summarized by Webb and Strong (2011).

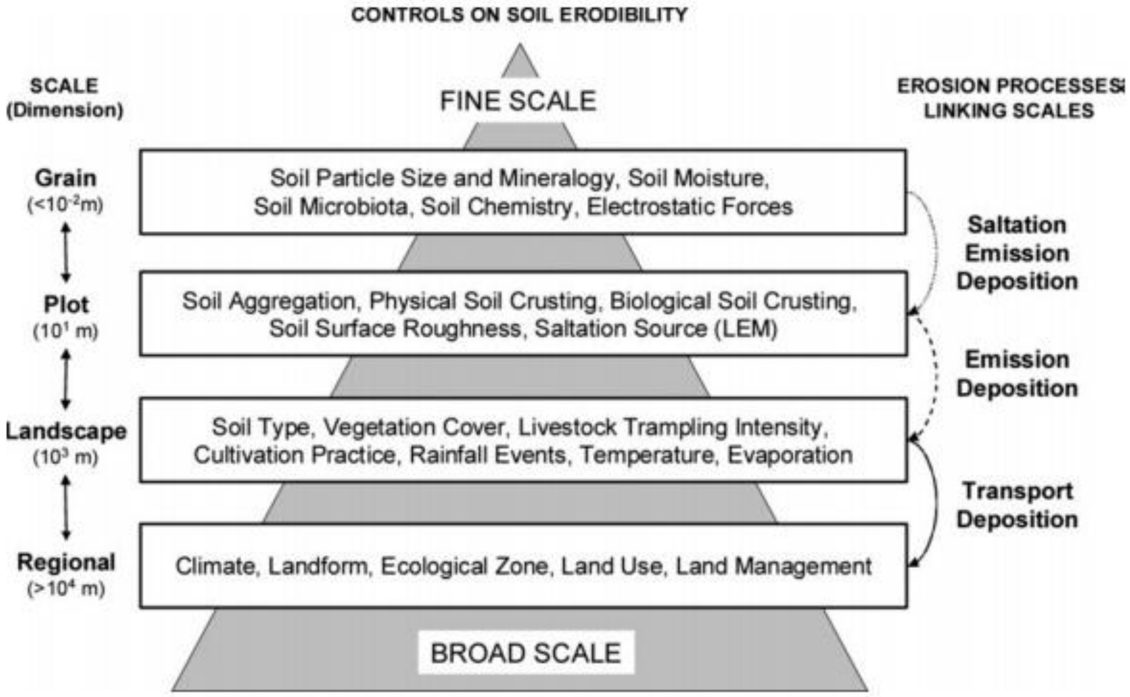


Figure 1. 1: Controls of soil erodibility (Webb & Strong, 2011)

1.2. Natural Dust Sources: A Review

Source regions have been the focus of numerous global studies (Prospero *et al*., 2002; Washington & Todd, 2005 and regional scale) which stated the importance of inland basins as major large-scale dust emitters. One of those basins is the Lake Eyre Basin (LEB) in Australia. It is stated by (Habeck-Fardy & Nanson, 2014) as one of the largest internally drained basins in the world. The Bodele depression in the in the Sahara (Washington, *et al*., 2006) is one of the largest sources in the world. Both systems are home to different supply, availability and transport limitations.

Bullard *et al*. (2011) identified additional geomorphic surface types which are commonly found in arid and semi-arid regions such as smaller dry lake surfaces, sand deposits, stony surfaces, alluvial deposits, and loess as listed in Table 1.1. The dust generation potential from these surfaces varies and is largely determined by the sediment texture. Mixed sand and gravel is too coarse and supplies no dust as would be the case for stony surfaces for example. Silt and gravel environments such as alluvial fans would also be less dusty source. Sand dunes may be unprotected and mobile and potentially emissive. The sources with the highest emission potential have a mixture of fines and sand. Such conditions are met in many fluvial settings. Fluvial environments that have mostly fines such as clay and silt are less likely to emit. These varied sedimentary environments have different supply characteristics with varied supply of fines as well as varied availability characteristics dependant on their sedimentary texture. Especially sand and silt/clay combinations are emissive because of the additional sand in the system which may act as saltation agent, a key driver in the suspension process. In addition to the texture which determines supply and availability other factors may act as supply limitations such as roughness, crusts and moisture (Webb and Strong 2011).

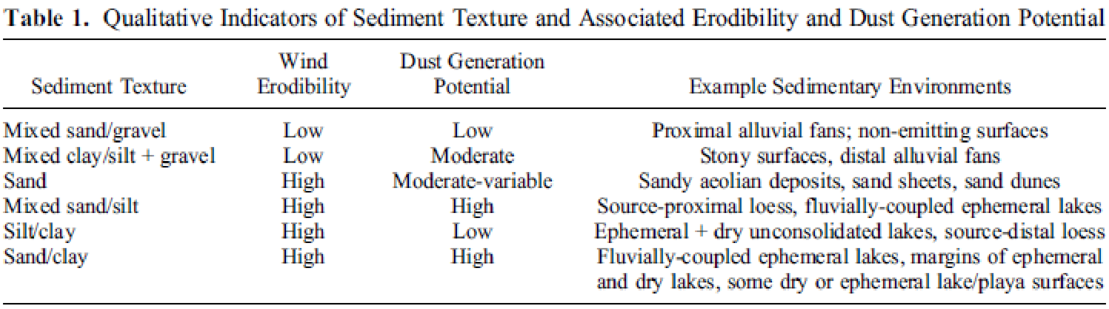


Table 1. Qualitative Indicators of Sediment Texture and Associated Erodibility and Dust Generation Potential

Sediment Texture	Wind Erodibility	Dust Generation Potential	Example Sedimentary Environments
Mixed sand/gravel	Low	Low	Proximal alluvial fans; non-emitting surfaces
Mixed clay/silt + gravel	Low	Moderate	Stony surfaces, distal alluvial fans
Sand	High	Moderate-variable	Sandy aeolian deposits, sand sheets, sand dunes
Mixed sand/silt	High	High	Source-proximal loess, fluvially-coupled ephemeral lakes
Silt/clay	High	Low	Ephemeral + dry unconsolidated lakes, source-distal loess
Sand/clay	High	High	Fluvially-coupled ephemeral lakes, margins of ephemeral and dry lakes, some dry or ephemeral lake/playa surfaces

Table 1.1: Indicators of sediment texture and associated erodibility and dust generation potential (Bullard, et al., 2011).

1.2.1. Natural Global Dust Sources

Natural dry inland lake depressions can produce and store much fine material. The Bodele Depression for example in the Northern Hemisphere is situated in Chad and is a source of dust that has been studied intensively. The Bodele Depression is estimated to produce about half of the mineral aerosols that are emitted by the Sahara, which is the largest dust source worldwide (Washington, *et al.*, 2009) and remains a major contributor of dust throughout the year

(Washington, *et al*., 2006) due to the persistent dry windy conditions in the Sahara. The Bodele Depression is also characterised by highly erodible sediments and strong erosive wind. The dust plumes found in the Bodele Depression are said to come from exposed dry diatomite lake bed which when combined with sand from mobile dunes is able to generate much dust. In short, the supply of fine material is great and there is no limit on its availability. The Lake Eyre Basin (LEB) is also emissive but given its semi-arid setting is often wet and inundated (Habeck-Fardy & Nanson) with water and as a result, while also important, less emissive than the Bodele. This more complex and dynamic system is also (Bullard & McTainsh, 2003) composed of sedimentary settings such as clay pans, alluvial channels, and ephemeral lakes, (Bullard & McTainsh, 2003). At the LEB supply of sediments is not always available given the moisture content and precipitation which is to be taken into consideration for most dust sources.

The combined role of climate, topography and other geomorphic factors determine the emission potential and the supply of fine suitable sediment being only one factor. Perennial lakes may contain sediments suitable for wind erosion, but the presence of water means that the system is availability limited. Perennial lakes can be an efficient trap of fine sediments and hold a detailed record of past periods. (Muhs, *et al*., 2003) They are also potential future dust sources if fully or partially desiccated (Gill, 1993). Hence ephemeral lakes may become important dust sources globally. In general, these lakes have been perennial at some stage in the past, and thus contain accumulated considerable quantities of fine-grained material of fluvial, groundwater derived and biogenic origin.

Once fine material has been generated and supplied and becomes potentially available, transport may take place. The major drivers of dust emission in Australia are the frontal systems (McTainsh & Leys, 1993). Three wind systems are clearly recognised as the dust producing winds in Australia. The pre-frontal winds are usually strong enough to raise dust in advance of the front across the continent of Australia. Once the front arrives, it is usually associated with strong and well-developed winds which ascend large quantities of dust. The westerly winds can raise the dust for a prolonged period (Leslie, *et al*., 2007). The westerly winds are usually characterised by rolling dust storms in the LEB and this tends to produce Australia's largest dust storms (McTainsh, *et al*., 2004; Leys, *et al*., 2011). The last wind system is the southerly winds which occur after the front has passed. These winds are also strong enough to lift the dust to cause it to be held in suspension. Similar transport controls will be at plays in most semi-arid settings.

The Bodele and LEB are among the largest dust sources in the world. In Southern Africa, a number of natural dust sources have also been identified. According to a study conducted by Vickery, (2013) as shown in figure, 1.3 below, between 2005 and 2008 significant dust plumes were noticed in Botswana and Namibia as well as South Africa.

These include the two large basins such as the Makgadikgadi pan and Etosha pan which are comparable to the LEB (White & Eckardt, 2006). These Makgadikgadi is situated in the middle of the dry savannah of north-eastern Botswana (White & Eckardt, 2006). The Makgadikgadi covers about 37 000 ㎢ and is an extensive pan complex (Bryant *et al.,* 2007 and Vickery, 2007); Cooke (1979) is a large inland un-vegetated ephemeral basin with very fine sediments. The site has fluvial, lacustrine and aeolian sediments (Vickery, 2007). The largest pans in the Makgadikgadi are Ntwentwe and Nxai Pans. According to Holmes *et al.,* 2012, dust storms that emanate from pans are usually observed in late winter. They are seasonally covered with water and grass and have a salty clay crust most of the year (White & Eckardt, 2006). According to Bryant *et al.* (2007), the site is part of lake Paleo-Makgadikgadi and is one of the largest Paleo-lake systems in Africa. Prospero *et al,* 2002 has identified the Makgadikgadi as the 9th most significant global dust source and the most significant dust source when it comes to Southern Africa.

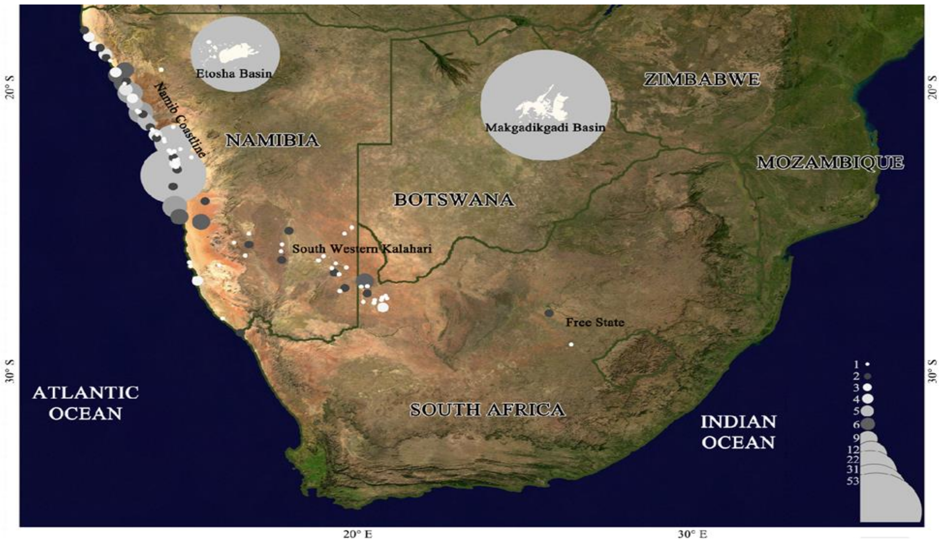


Figure 1. 2: Location of dust plumes in Southern Africa (2005-2008). (Source, Vickery, 2013)

The second major source in Southern Africa is situated in the eastern part of the North semi-arid part of Namibia is the Etosha pan which has a surface area of about 5000-6000㎢. The surface of the Etosha pan is characterised by saline silt, clay and sand (Bryant, 2003). The water table in the Etosha pan is usually close to the surface. Most of the water that enters the Etosha pan comes from a network of channels. For the most part of the year, the pan is sparsely vegetated and characterised by fine-grained sediments. Because of the availability of both sand and silt material in the pan, this makes the Etosha pan to be one of the most important dust sources in Southern Africa. Bryant (2003) conducted work in the Etosha pan from 1997-2002. According to (Bryant, 2003) the emissions in the Etosha Pan have been compared to other worldwide dust sources such as the Australian LEB. Numerous other smaller sources in Figure 1.2 relate to small pans and dry rivers many of which are found along the west coast. Inland sources are also pans including those in South Africa. Many areas are dust source free.

1.3. Anthropogenic Dust Sources

Anthropogenic sources tend to be much smaller in scale and impact compared to the large natural dust sources. These sources also emit fine fraction with less than 25µm (Li, 2008).

According to Scorgie (2001) and Anon (1999), anthropogenic sources that are a result of human activities have what is known as stationary sources. They include agricultural activities where there is soil tillage, crop burning and application of fertilizers. Mining activities also result in emissions because of the drilling and blasting. Residential activities include combustion of coal.

1.3.1. Agricultural Dust

Agriculture represents a major industry worldwide (Tanrivermis, 2002). Following the industrial and green revolutions of the 19th and 20th centuries, agriculture began to have negative impacts on the environment (Tanrivermis, 2002). Farming techniques gradually spread and agricultural tools and practices became easier to use and more efficient. Agricultural chemicals, machinery, and high-yielding crops and animals began to be used in agriculture for high profitability (Nicholson *et al.*, 2003). These advances changed the structure of production, and market-oriented or commercial farming gained importance, so enhancing trade in food and agricultural products. Agricultural activities can be considered a significant contributor to particulate emissions through tilling, harvesting and other activities associated with field preparation (Galloway *et al.*, 2008). Many of these emissions are local in nature and detrimental to the nearby environment.

The need to increase agricultural productivity increased land-use intensification. This encouraged industrialization and agricultural mechanization. Over time the techniques that were used for farming were gradually increasing resulting in easier farming ways. Around the 20th century, there has been a very rapid use of land (Galloway *et al.*, 2008). This is due to the implementation of heavy machinery and many other agricultural tools and practices that have become easier and more efficient. However agricultural areas are also home to larger dust storms (Galloway *et al.*, 2008)). Dust storms are described as a natural phenomenon. They happen on their own however human activities influence and escalate them. According to Wang (2005), dust storms are a natural phenomenon if they happen because of the three conditions, (1) "strong winds", and (2) "cyclone movement", (3) "a dry, loose and bare sandy soil". Dust storms are a result of turbulent winds raising large quantities of dust into the air and reducing visibility to less than 1000m (O'Loingsigh *et al.*, 2014). Zhang *et al*. (2001), states that dust storms occur the most in deserts and the areas surrounding them. Song (2005) adds that also in many arid and semiarid regions dust storms are likely to occur. The increasing occurrence of dust storms worldwide is a result of many attributes. These range from dry and stormy weather conditions to overgrazing and increasing human activities that put pressure on the land. Overstocking and overgrazing have been implicated mostly when it comes to dust storms (Zhou, *et al*., 1993). According to (Wang, *et al.*, 2005) dust storms have become an increasing environmental problem and continue to threaten the productivity of agriculture. Wang states that according to a survey in 2000, the area that was affected by wind erosion resulting in dust storms in China was about 20% of the total land. The intensification of soil cultivation in the area has led to the dramatic increase and expanding dust storms.

South Africa is also home to agricultural dust especially in the Free State Province which lies in between the transition zone of South Africa's sub-humid temperate grassland to the east and the semi-arid Karoo and the arid Kalahari to the south and the west. The Province experiences 500mm or less of rainfall and it has a widespread of environmental practices such as agriculture (Wiggs & Holmes, 2010).

The Free State region is subjected to the macro-scale atmospheric circulations which control the climate of central Southern Africa (Wiggs & Holmes, 2010). The strong winds that occur late in winter and early in spring are responsible for the localised dust storms and dust plumes emerging from pans and agricultural land (Holmes, *et al.*, 2008). This suspension of aeolian dust is most common in months August to October. The Free State Province has a soil content of red sandy soils and clay soils with high nutrients (Mahasa, 2015). According to Wiggs and Holmes, (2010) and Hensley *et al* (2006), the agricultural land potential derived by the west-central and western Free State is classified as either very low potential or non-arable. Wiggs & Holmes (2010) indicates that commercial drylands comprise 30% by area and about 57% is unimproved grasslands from the total area of 108 544 hectares that the study covered.

1.3.2. Mining activities in South Africa

Though agricultural activities have been looked as the major culprits when it comes to dust emissions throughout the world, mines also play a significant role. According to Wright *et al.* (2014), the mining industry is a major economic activity for developing countries. These mining activities entail disruptive environmental conditions and may have adverse impacts on the communities that are surrounding them. The South African mining sector has had a great impact on the economic development of the country and there have been both positive and negative impacts when it comes to the environment. In mineral mining sites dust is usually generated during excavation, transportation and mineral processing operations. Dust generation is influenced by material properties, such as hardness, particle size distribution, particle density and moisture (Wentzel, 2015). How the dust particle will behave in the atmosphere differs because of the different forces that act upon the different sized dust particles. The Witwatersrand gold rush commenced in 1886 and produced up nearly 300 tailing dams (Matoane, 2014). Tailings are mud like materials and are leftovers or waste from mines. The gold mine tailings usually found in South Africa consists of heavy materials such as zinc, copper and arsenic (Wright, *et al.*, 2014). The source of air pollution in the areas of Krugersdorp, Kagiso, and Davidsonville in the Gauteng Province are the gold mine dumps and the tailing dams as most of them are not covered. There have been heavy suggestions that these mine dumps and tailing dams are dust nuisance during periods of high winds for the local communities (Wright, *et al.*, 2014).

1.3.2.1. Opencast Coal Mines in South Africa

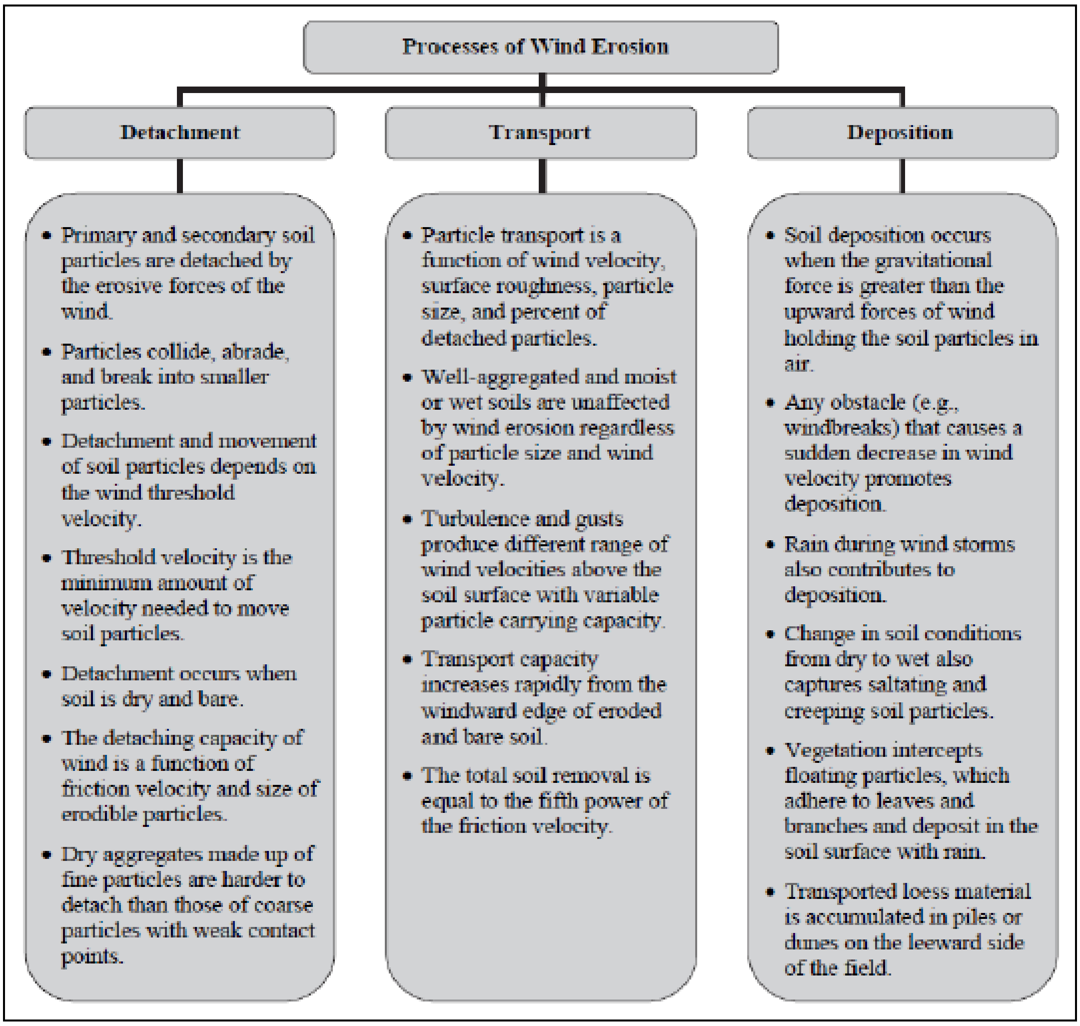
Dust has been and remains a well-known challenge through the years in the coal mining sector. The dust characteristics that arise from the coal mining environment have different impacts on different geographic areas (Wentzel, 2015). South Africa has 65 coal mines in the Mpumalanga Province alone (Finkelman, *et al*., 2002). This indicates that the mining sector faces many hazardous challenges and one of them is coal dust.

When coal seams are close to the surface, opencast mining methods are used to extract the coal. This recovers a great portion of the coal as compared to underground mining (Scott *et al.*, 2010). The topsoil is removed in the area that is to be mined removing the flora and the fauna as well. This results to bare ground. The drilling and blasting that follows the removal of topsoil loosens the exposed bare soil. Once the coal is exposed, drilling and fracturing of the coal will take place by means of explosion. During this process, coal and dust are being emitted into the atmosphere (Wentzel, 2015).

1.4. From soil and sediments to dust

Dust can be defined as the fine particles of matter which are found in the atmosphere and they come from different sources such as soil (Merriam & Tisdell, 2015). The IUPAC, (1990), defines "Dust: Small, dry, solid particles projected into the air by natural forces, such as wind, volcanic eruption, and by mechanical or man-made processes such as crushing, grinding, milling, drilling, demolition, shovelling, conveying, screening, bagging, and sweeping. Dust particles are usually in the size range from about 1 to 100 µm in diameter, and they settle slowly under the influence of gravity." According to Hesse *et al.* (2003), soils are not made up of just one or two components. Each type of soil has different chemical and physical components, making them very complex materials.

The tillage of soil particles results in the loosening of soil particles. During the process of dust formation, the soil detaches from the land surface as it is lost because of either anthropogenic factors or natural phenomenon (Fox, *et al*., 2012). According to Blanco & Lal (2008), these soil particles are transported and deposited at a distance. The agent responsible for the transportation and deposition could be wind or water. In the case of wind, Sankey *et al*., (2011) provide three stages of wind erosion, namely detachment, transport and deposition. How the suspended soil particles move and are deposited depends on their size, say (Blanco & Lal, 2008). As a result of this, the bigger the size of the particle, the quicker it settles down leaving small particle as dust, concludes (Wang & Lai, 2014).



Processes of Wind Erosion

Detachment

- Primary and secondary soil particles are detached by the erosive forces of the wind.
- Particles collide, abrade, and break into smaller particles.
- Detachment and movement of soil particles depends on the wind threshold velocity.
- Threshold velocity is the minimum amount of velocity needed to move soil particles.
- Detachment occurs when soil is dry and bare.
- The detaching capacity of wind is a function of friction velocity and size of erodible particles.
- Dry aggregates made up of fine particles are harder to detach than those of coarse particles with weak contact points.

Transport

- Particle transport is a function of wind velocity, surface roughness, particle size, and percent of detached particles.
- Well-aggregated and moist or wet soils are unaffected by wind erosion regardless of particle size and wind velocity.
- Turbulence and gusts produce different range of wind velocities above the soil surface with variable particle carrying capacity.
- Transport capacity increases rapidly from the windward edge of eroded and bare soil.
- The total soil removal is equal to the fifth power of the friction velocity.

Deposition

- Soil deposition occurs when the gravitational force is greater than the upward forces of wind holding the soil particles in air.
- Any obstacle (e.g., windbreaks) that causes a sudden decrease in wind velocity promotes deposition.
- Rain during wind storms also contributes to deposition.
- Change in soil conditions from dry to wet also captures saltating and creeping soil particles.
- Vegetation intercepts floating particles, which adhere to leaves and branches and deposit in the soil surface with rain.
- Transported loess material is accumulated in piles or dunes on the leeward side of the field.

Figure 1. 3: Three main processes of wind erosion (Blanco & Lal, 2008) .

Baxter *et al*., (2013) states that the transportation of soil particles also has three steps. They are saltation, surface creep and suspension. The size of the soil particle displays special traits when being transported during wind erosion. Soils that have particles less than 0,1mm are transported in suspension. Medium size particles (0,1mm – 0.5mm) is transported in saltation and larger particles (0,5mm – 2mm) are transported through creeping *(Blanco & Lal, 2008)*.

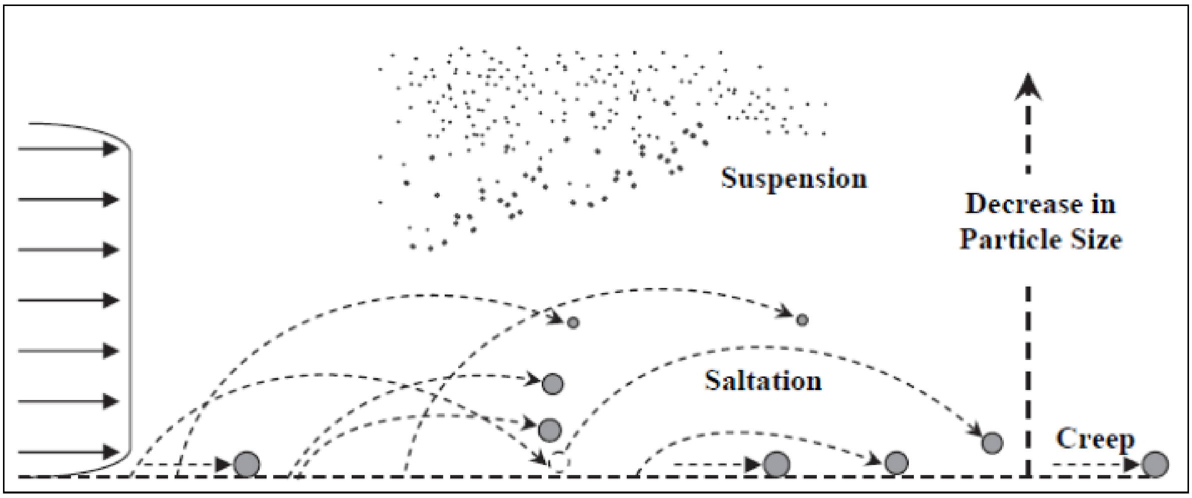


Figure 1.4: Modes of soil particle transport during wind erosion. (Blanco & Lal, 2008).

Dust emission is described by (Marticorena, 2014) as the "final product" of processes that are included in dust formation due to the wind. Therefore describing dust emissions means describing the physical processes involved (Marticorena, 2014) together with the environments that influence them (Marticorena & Bergamett, 1995) discuss the controls of dust emission. They state that dust is controlled by factors such as grain size, moisture, roughness and crust with wind playing a significant role in influencing the motion of particles. Once a particle is in motion as a result of wind erosion, its path depends heavily on its weight either weighing it in a downward motion or allowing it to be suspended into the atmosphere. During dust emission, particles are subjected to forces that hold them to the surface such as weight and interparticle forces. Large or heavy particles tend to move along the surface. The motion is known as creeping as shown in figure 1.4. Those particles with a diameter between 70 and 1000µm are entrained in a saltating motion. These particles will be ejected to the atmosphere for a short period of time and will come back to the surface (Marticorena, 2014). However, as the saltating particles hit back to the surface, their force is strong enough to overcome the binding forces that act upon them leading to dust emission. The suspended particles could result from either the impacted surface or disaggregation of the saltating grains, a process called auto-abrasion. This highlights saltation as a prerequisite of dust emission (Shao, *et al*., 2011). Production of particles smaller than 70µm in diameter result to entrainment by suspension, this is because their terminal fall velocity is lower than the vertical wind velocity.

As mentioned earlier, the fine material on its own cannot produce dust. This is also shown in the work of Bullard *et al*., (2011), where it states that it is a combination of both silt and sand material that has the highest potential of dust activity. Tegen and Lacis (1996) also looked at particle size and derived three major soil textures (sand, silt and clay). They concluded that particle sizes <0.002mm (clay) tend to stick and agglomerate to larger particles, leading to a decrease of sediments to be susceptible to the wind.

However, Desouza *et al*., (2015) shows that there was high dust flux found in Patiala, New Delhi and Kanpur because of the high clay content in the sand and silt loam soil types. This suggests each soil texture were present. For dust to occur in any environment, both sand and silt must be available in quantities enough for them to emit dust. According to Marticorena (2014), it is the fine particles that are emitted into the atmosphere as a result of wind erosion in semi-arid to arid regions that result to dust. Marticorena describes soil roughness, soil moisture and size distribution as key role players of soil characteristics when it comes to the emission of dust, because they control how frequent dust events are to occur in a particular area. The smallest fraction can easily be uplifted and transported long-range.

1.5 Study rationale

This is the first study dedicated to examining the sources of South Africa’s major dust sources. An early study examining the dust plumes between 2005 to 2008 by (Vickery *et al.*, 2013) for Southern Africa, showed only a few dust plume locations in Southern Africa where the Free State had the least occurrence of the plumes. A follow-up unpublished survey covering the period of 2006 to 2016 of South Africa's dust sources was conducted using Meteosat imagery (Eckardt pers. comm.). The results show frequent dust storms recorded in the Free State with an increase towards 2016. It is from these unpublished results where the aims and objectives of this study arise. Because dust is an environmental concern that cannot be ignored and threatens agricultural productivity, it is important to look at the surface controls or characteristics that lead or promote dust production. This study seeks to understand the role of the surfaces towards dust production.

1.6. Aims and objectives

Aims: Characterising South Africa’s Major Dust Sources

Objectives:

1) Identify South Africa’s major dust sources using an existing MSG source record.

2) Identify the soil texture of South Africa’s major dust sources.

3) Describe the physical soil characteristics of South Africa’s major dust sources.

2. SOUTH AFRICA'S MAJOR DUST SOURCES, SURFACES AND SOIL TYPES

2.1. Introduction

Many studies in the Southern Africa region (Vickery, 2013 and Bryant, 2003) have used GIS and remote sensing together with fieldwork observations to asses dust emission. This is a preliminary observation at South Africa's major dust sources from an existing MSG record and it is a first national dust survey of this kind (Eckardt pers. comm.). At this stage, not much is known about the surface controls of the regions, however by using this record this thesis seeks to understand the possible contributing factors that could explain the occurrence of South Africa’s major dust sources and events.

2.2. Research Design

The main goal of the research is to characterise the major dust sources in South Africa by examining associated source surfaces and the soil types. This research is divided into two major approaches, GIS approach and field sample analyses. Chapter 2 focuses mainly on the GIS techniques looking specifically at soils and land use respectively. Different shapefiles with different characteristics for the study area were collected as elaborated below. The research methodology of this study is based on GIS which allows for the management, analysis and interpretation of huge datasets allowing informed decision making that can also be used in South African dust studies (Meshesha *et al.*, 2012).

2.3. Data layers use

2.3.1. MSG dust source point

This study is based on a preliminary unpublished research data making use of dust observations from satellite data collected between 2006 and 2016 for the Southern African domain. This yet unpublished study uses Meteosat imagery to generate an event dataset of dust sources points for South Africa. In this study, we try and attribute these identified events to surfaces from which the plumes were seen to emanate. Due to the spatial resolution of the MSG data and the uncertainty of dust source mapping, a 10 km radius buffer was added to the individual points. These points and buffers are used to establish the national province from which the dust plumes come from, the landcover in the source areas and soil types associated with those events and plumes. This results here focus exclusively on the South African domain even though sources in the event catalogue also include the neighbouring countries, which are not considered here in this study.

2.3.2. National Geospatial Information Land Cover Map

Landcover maps have been used multiple times in a variety of disciplines. The study uses land use and land cover maps to locate the MSG points on them and what role does land use and land cover has concerning dust emission in South Africa. Data on land-use and land cover change are available from cadastral surveys, agricultural census, digitized maps and remotely sensed data. Land cover and land use maps are vital to produce information worldwide. The dataset for this study was obtained from the National Geospatial Information (NGI), division of Rural Development and Land Reform in Cape Town. The data is known as the 72 Class GTI South African National Land Cover Dataset (2013/2014), (Land-Cover Dataset Report., 2014). The dataset was created by GEOTERRAIMAGE (GTI). According to the report, the dataset is based on a 30×30m resolution. The dataset was acquired between April 2013 and March 2014. The 30m resolution Landsat falls within the period of the MSG data was very helpful because its time period corresponds with the peak time, during a period when most of the dust events are recorded in South Africa. (See Appendix, A2.1).

2.3.3. African Soil Atlas Map

A layer of the African soil atlas map (2014) was used in this study to identify the types and forms of soil that are present in source areas. The soil map shows the soil classes at a continental scale and has a projection of WSG 1984. South African soil maps were also observed in this study. There were great similarities between these maps. However, due to the better and well documentation of the African soil map, it was then preferred for the completion of this study.

The African soil map was put into ArcMap 10.3. This was performed for the purpose of looking for the most or the frequently appearing soils in the source area and South Africa as a whole. ArcMap has a clip tool and merge tool found in the toolbox section of the software. Once the layer was clipped, it was merged with the layer used to clip so that the information from both layers was kept and they correspond to the original data. The results and findings are presented in the next chapter in the form of charts, graphs, and maps. These soils will also be discussed in detail on their contribution to dust production in South Africa. This was significant because the study seeks to understand the soil properties that contribute to the production of dust. Desouza *et al.*, (2015), uses similar methods to highlight dust emissions from different soil types in the Northwest and Indo-Gangetic plains of India. The method identifies areas of maximum dust activity. Other similarities between the two studies include both the study areas being arid regions and abundant with sandy soil types. The study areas are also characterised by similar climatic conditions, dry and hot summers and cold winters (Desouza, *et al.*, 2015).

2.4. Results

This section presents the results and findings of the study. Maps, graphs, tables, charts and descriptive text will be used to address and present the results. Various soil types, land use, and land covers are some of the variables that were investigated in the study. These results will attempt to address objective 2 which seek characterise the sources of South Africa's major dust sources.

2.4.1. Meteosat Second Generation (MSG)

The MSG satellite analyses and results (Eckardt pers. comm.) was used to establish dust source locations in South Africa. The MSG has a temporal resolution of 15 minutes and begins from 2006 to 2016.

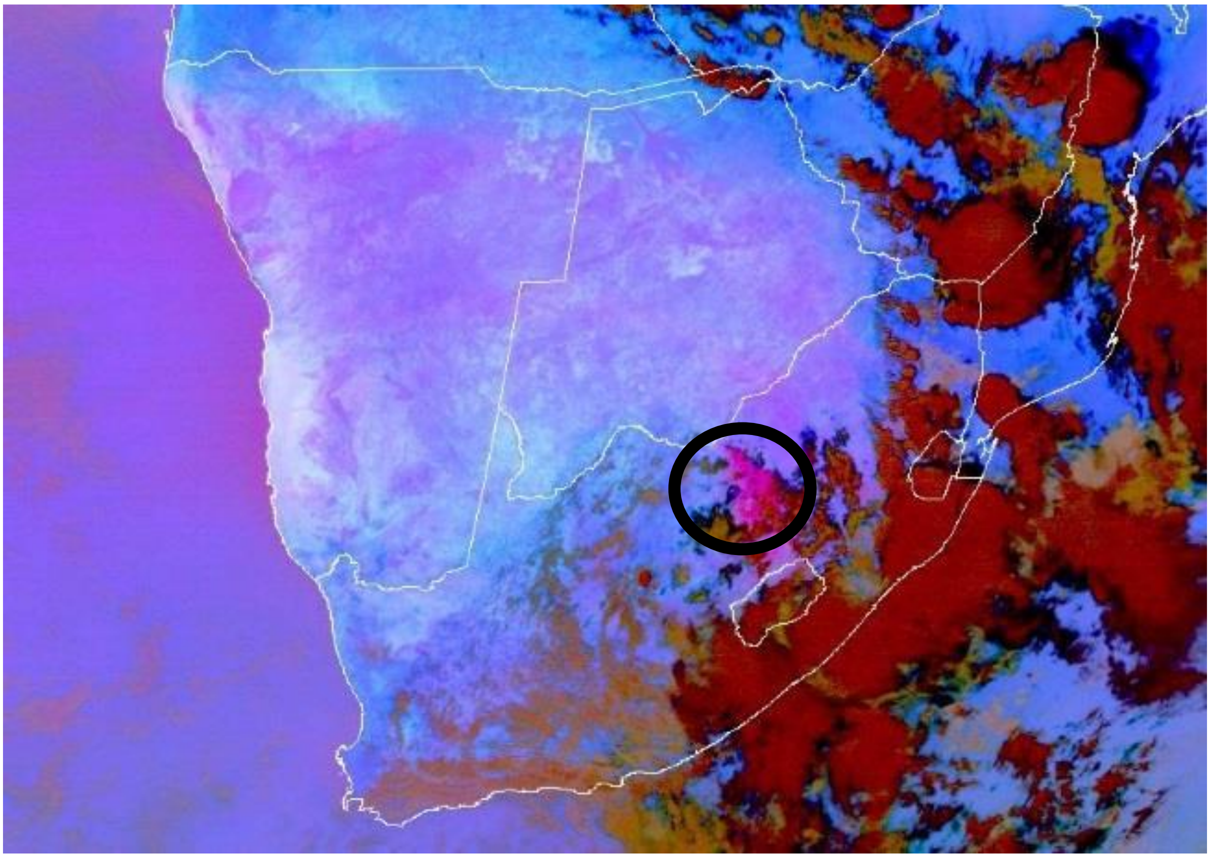


Figure 2. 1: A typical MSG image with dust plume in pink in a black circle.

The same MSG data is also currently subject to a temporal and climatic analysis as part of another MSc (F. Mogane in preparation). This study here focuses on the surface characteristics component and feeds into a bilateral Swiss / South African National Research Foundation (NRF) funded project.

2.4.2. Location of MSG points in South Africa

Using a heat map (figure 2.2a) areas of frequent dust events are indicated by red. Further details on creating a heat map can be found in Appendix 2 (A2). The MSG points recorded in South Africa between 2006 and 2016 fall mostly between two provinces of the country, namely Free State and North West Provinces. What remains unknown at this point and what the study seeks to find out are the surface characteristics that cause the frequent events in these parts of the country.

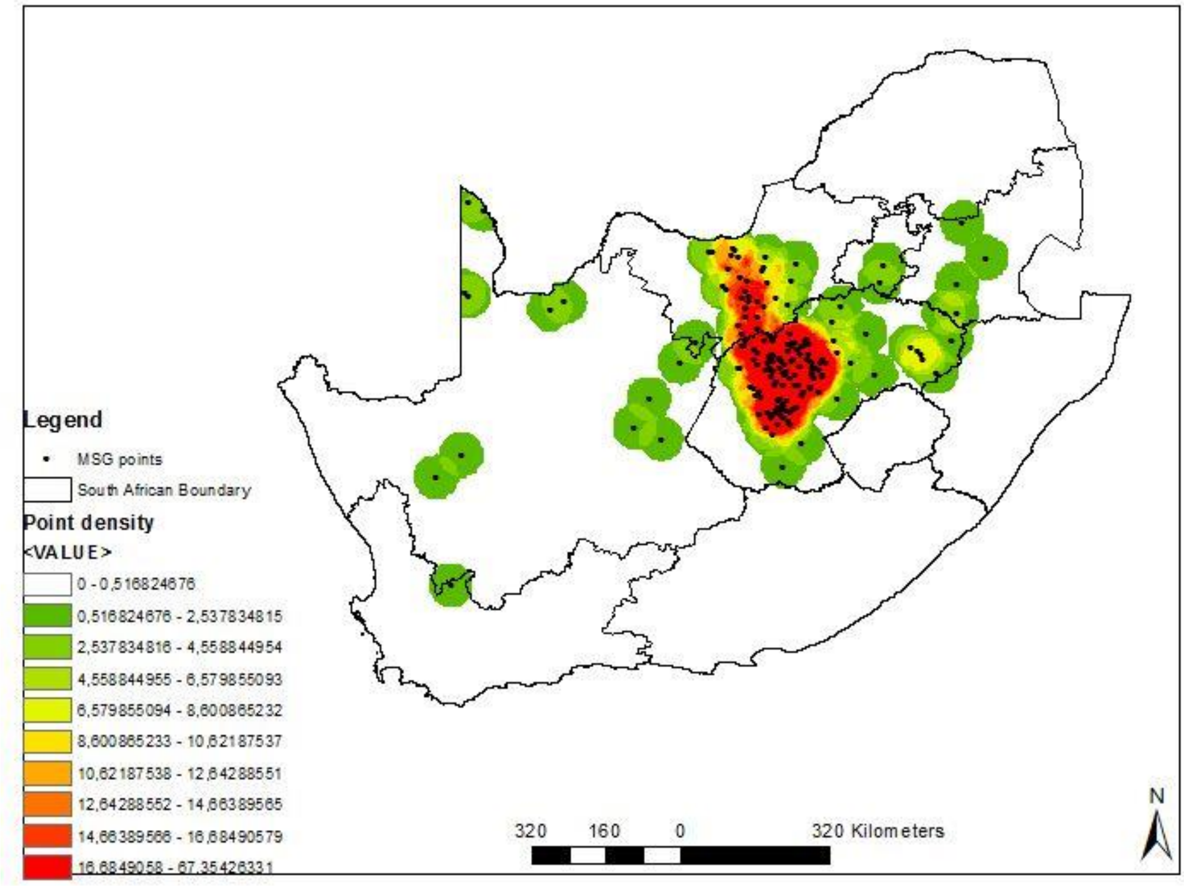


Figure 2.2a: Shows the distribution of the MSG points (Eckardt pers comm 2019). Most of the points fall on the Free State Province and on the North West province. (See Appendix, table A2.1 for raw data).

The point data, in this case, dust event sources, were interpolated to produce a density surface. Heat maps are used to visualise point data and they help in identifying clusters of high and low values. The legend in the above map shows the value of point density in different parts of South Africa. As indicated above, areas of high values are shown by the red colour and they indicate frequent dust storm occurrences. Figure 2.2b shows the distribution of MSG points or dust event count across the all the Provinces of South Africa.

Free State (FS) as seen in the figure had the highest number of dust events with over 120 events (71%) in the past ten years. North West Province (NW) follows exceeding 20 dust event (27%) occurrences during this period. The Northern Cape (NC) takes the third position of about 10 occurrences.

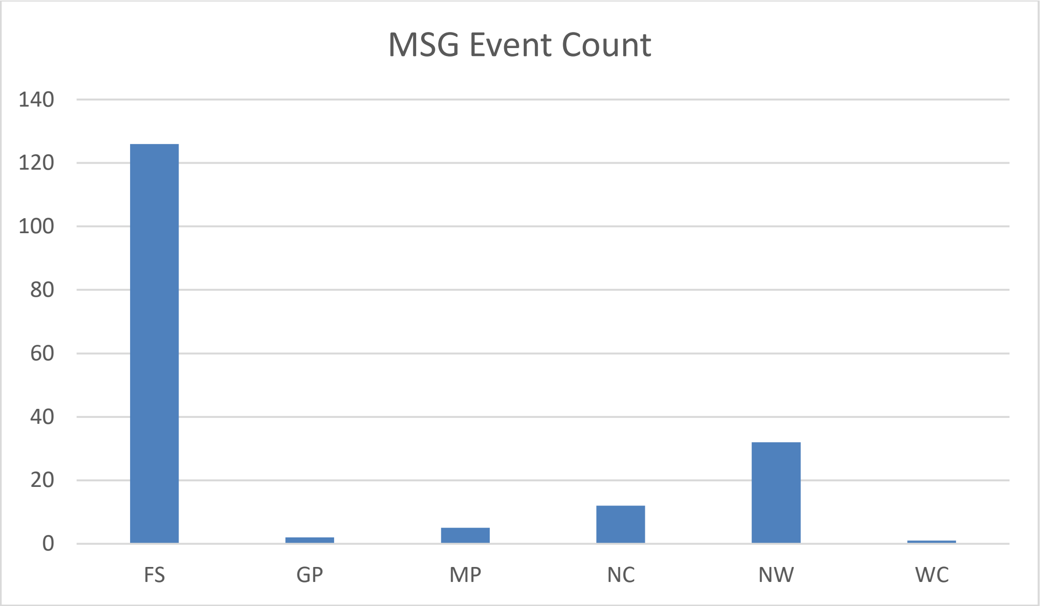


Figure 2.2b shows *the distribution of the MSG points in relation to SA provinces. Most of the points fall on the Free State Province followed by North West Province, Northern Cape, Mpumalanga, Gauteng and the Western Cape Province respectively.*

What is interesting is the lack of dust events in the other parts of South Africa. Very few dust events were noted in the Western Cape (WC), Mpumalanga (MP) and Gauteng provinces (GP) and the Eastern Cape (EC) and Limpopo were completely dust free.

2.4.3. Soils

The MSG points were also laid on the African soil map. Most of the points fell on the Luvisols, Arenosols and Lixisols of the Free State and North West (Source area) of South Africa as shown in figure 2.3a. Figure 2.3b shows the distribution of major soil types in South Africa and the Free State Province. The graph shows that these soil types are distributed all over South Africa but only the soils found in Free State and North West Provinces seem to be highly emissive.

50% of Luvisols are distributed in other parts of South Africa. However, the Free State Province is the most emissive province, but no other Province is as emissive as these dust sources. Also, South Africa is populated greatly by the Luvisols but results show that only those that are found in the Free State are emissive. Soils are therefore not the only control.

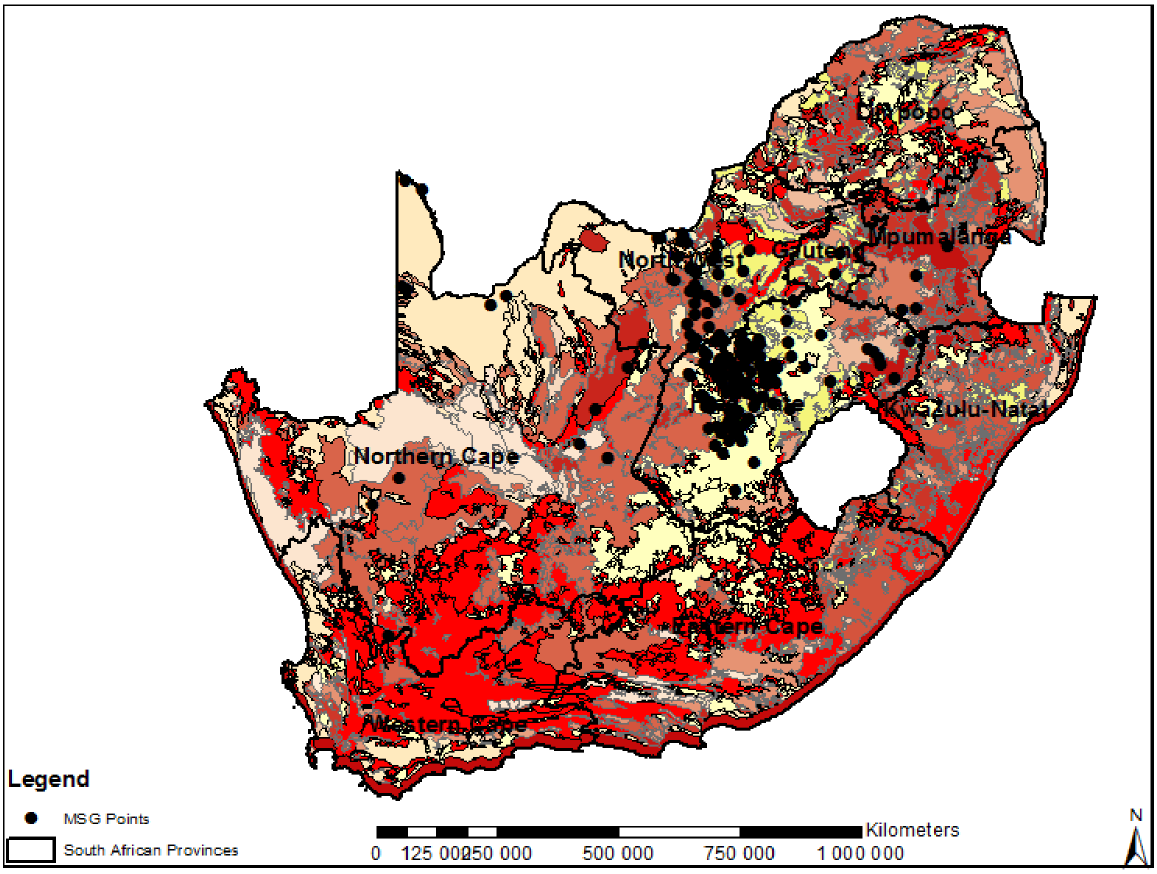


Figure 2.3a shows the distribution of the MSG points in relation to the African Soil Map. Most of the points fall on Luvisols, Arenosols and Lixisols. (Legend in the Appendix, figure A2.1).

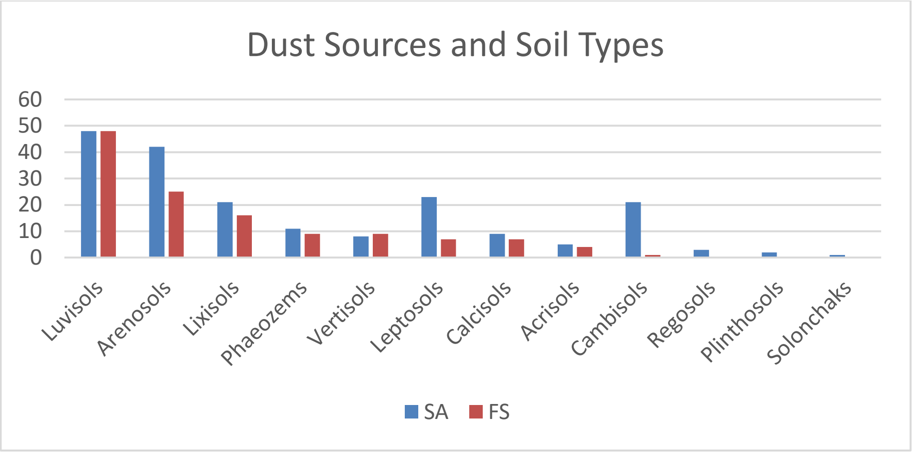


Figure 2.3b: Shows MSG point counts and soil types for South Africa (SA) and the Free State (FS). Luvisols and Arenosols are the most emissive.

2.4.4. Land use

Land use and land cover play a very important role when it comes to dust production as has been shown by previous studies. Unprotected bare land emits more than the covered land. This is because covered land in the form of grass, trees or shrubs act as a shield or resistance protecting the topsoil from wind erosion.

Figure 2.4 below shows the distribution of MSG points in relation to cultivated lands (green) and mines (red) in South Africa. A widespread of cultivated land is found throughout South Africa such as the Eastern Cape and the Western Cape Provinces. Nevertheless, little to no dust events are recorded in these provinces where there are also mines and cultivated land.

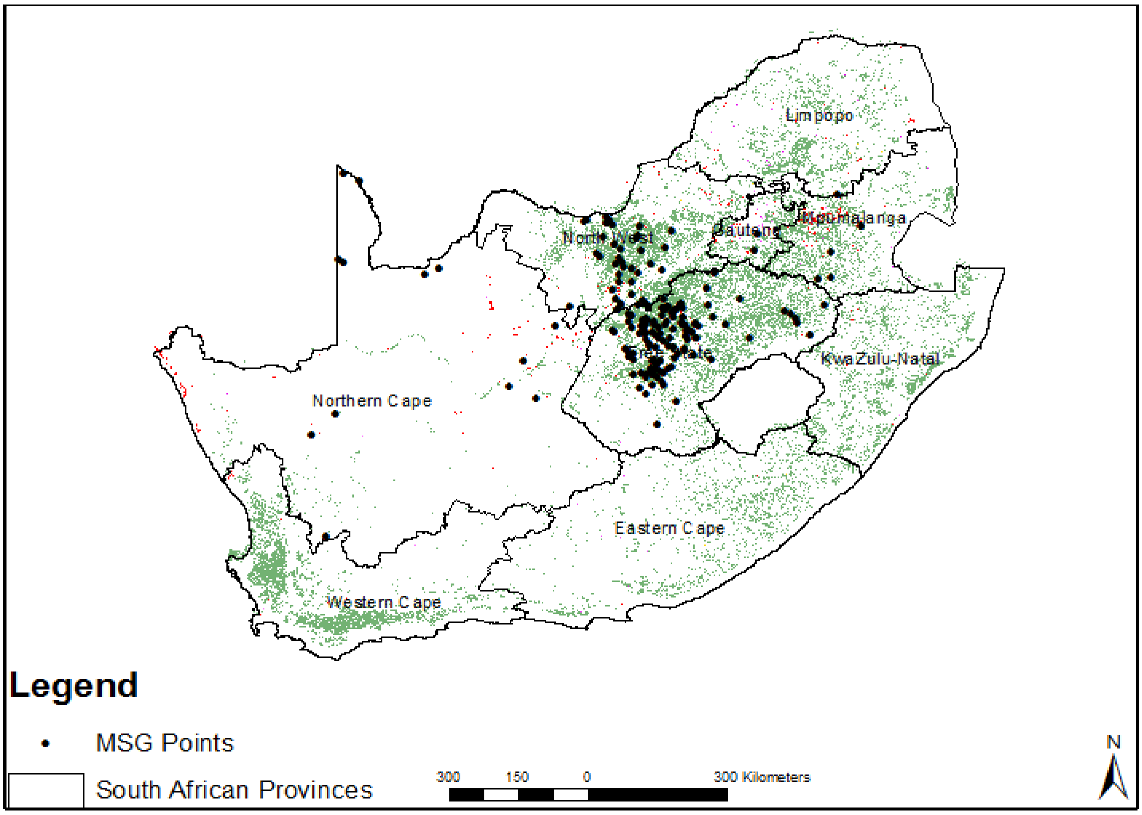


Figure 2.4: Shows the distribution of the MSG points in relation to cultivated lands (in green) and Mining areas (in red) in South Africa. Most of the points fall on the south western part of the cultivated lands in the interior of South Africa but not the Western Cape, Eastern Free State or Mpumalanga.

The role played by land use and land cover when it comes to dust production cannot be underestimated. Frequent tillage of the soil weakens the topsoil causing it to be more susceptible to wind erosion and less vegetate or barren ground is also more prone to wind erosion. Figure 2.5a shows the MSG dust events laid on a land use and land cover map. Most of the points lie on the agricultural lands (cultivated land to be more precise).

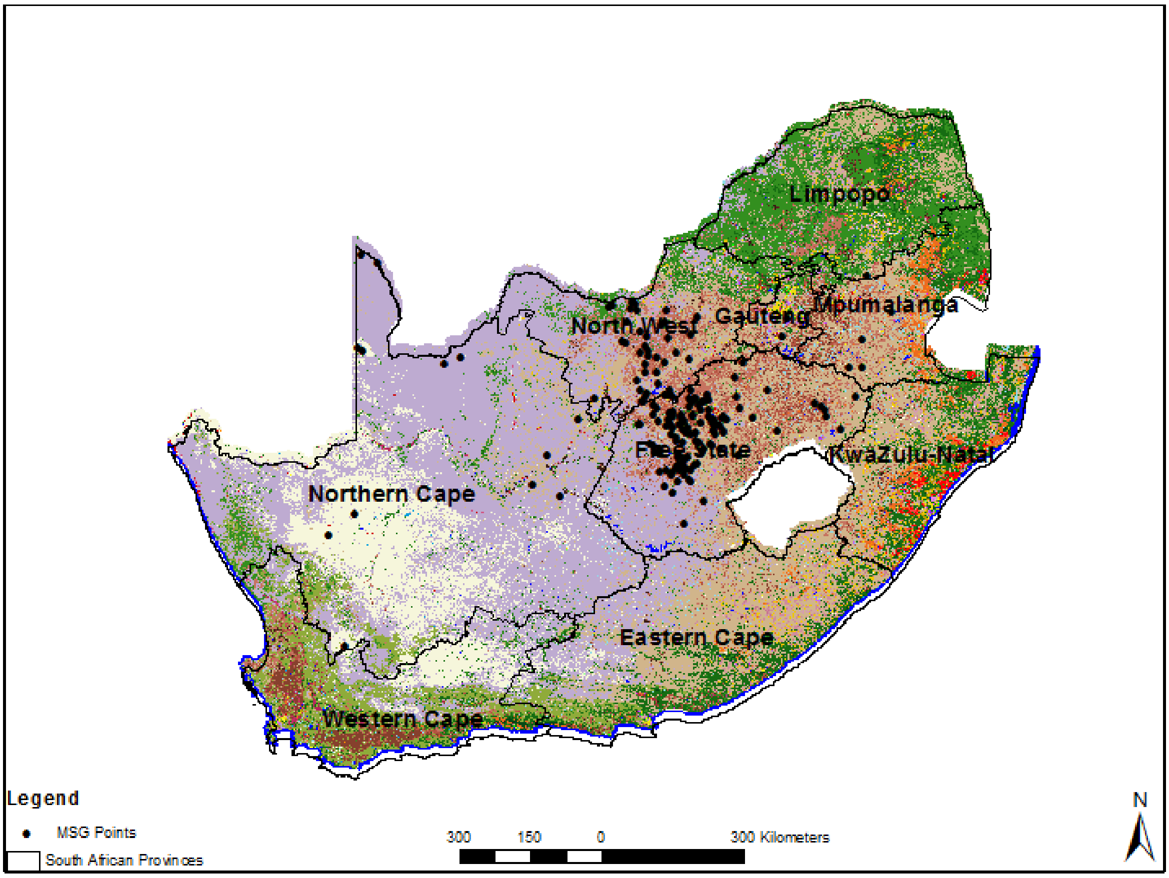


Figure 2.5a: Shows the distribution of the MSG points in relation to detailed South African land cover and land use map. The map was provided by the National Geospatial Information and has 72 classes. (Legend is in the Appendix, table A2.2)

The MSG point data together with the land use map were used to create 10km buffers for each of the multiple events using QGIS 2.16.3 this was done so that each point would be treated as an area rather than as a point. The national land cover dataset is based on 30×30m raster cells. Using the Geoprocessing tool, a fixed radius of 10km was used to create the buffer, the result of each point is a circular shape as shown in figure 2.5b

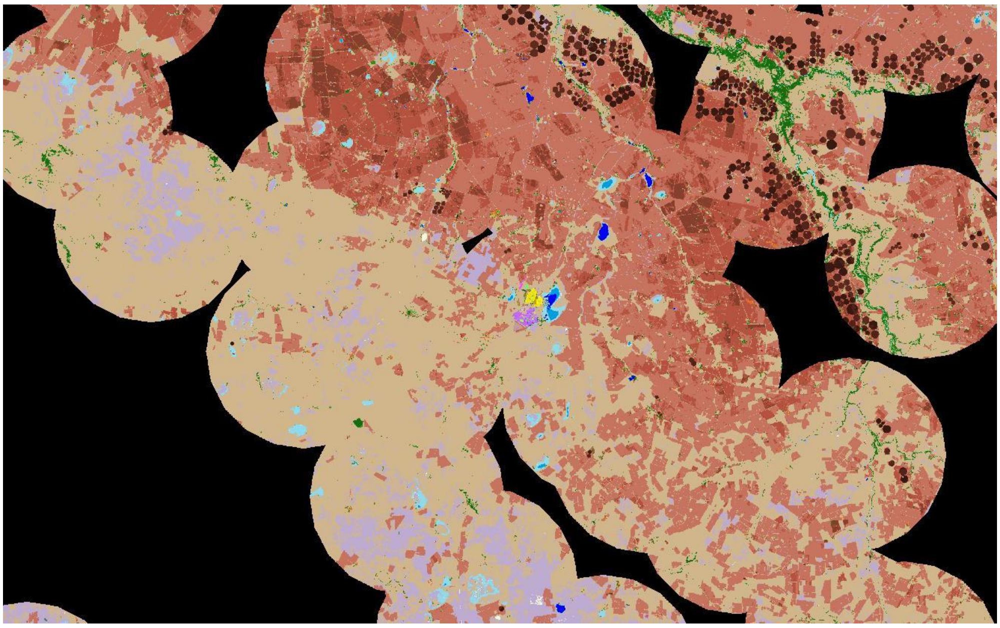


Figure 2.5b: Close up of 10km buffers for source points in the Free State. Source: NGI Data. The main areas included here are rain fed agriculture and grasslands. Bultfontein is at the heart of the figure. Also recognisable are riparian vegetation and centre pivots in the NE corner. (Legend is in the Appendix, TABLE A2.2)

The land cover and land use map show that South Africa is covered by natural surfaces such as grasslands, forests and shrubs, Figure 2.6a shows South Africa's land cover and land use between and 2013 and 2014. 81% of the total surface of South Africa is covered by natural surfaces followed by 13% of urban practices. Figure 2.7b shows the sources area where 10km buffers (figure 2.5b) and (table A2.2) of dust emissions were used to identify the percentages of land use and land cover. 61% of the total area of the source area is covered by the natural surface. Agriculture (see table A2.3 for details) comes second with 35% compared to the 13% of the whole country.

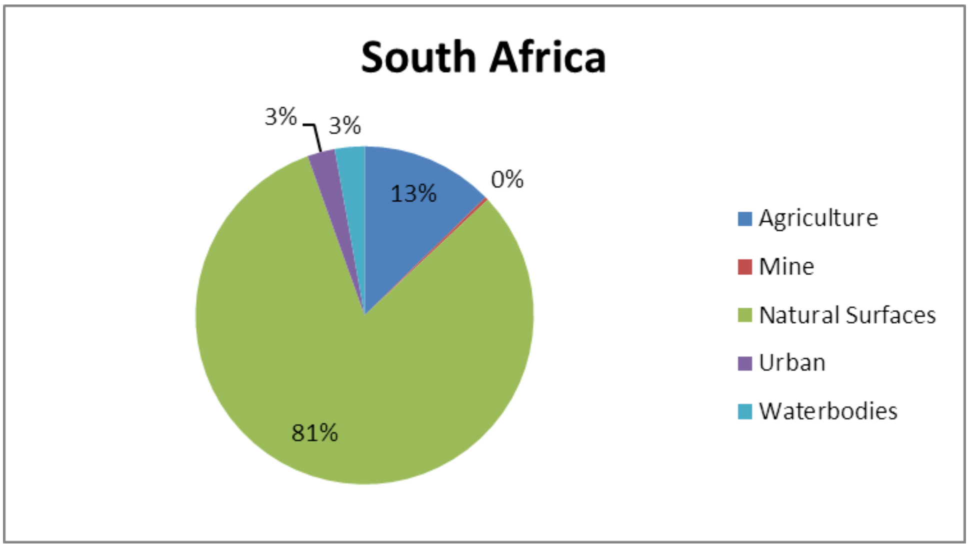


Figure 2.6a shows the South African Major land use and land cover classes. Refer to Appendix for detail, (TABLE A2.2) Source: NGI Data

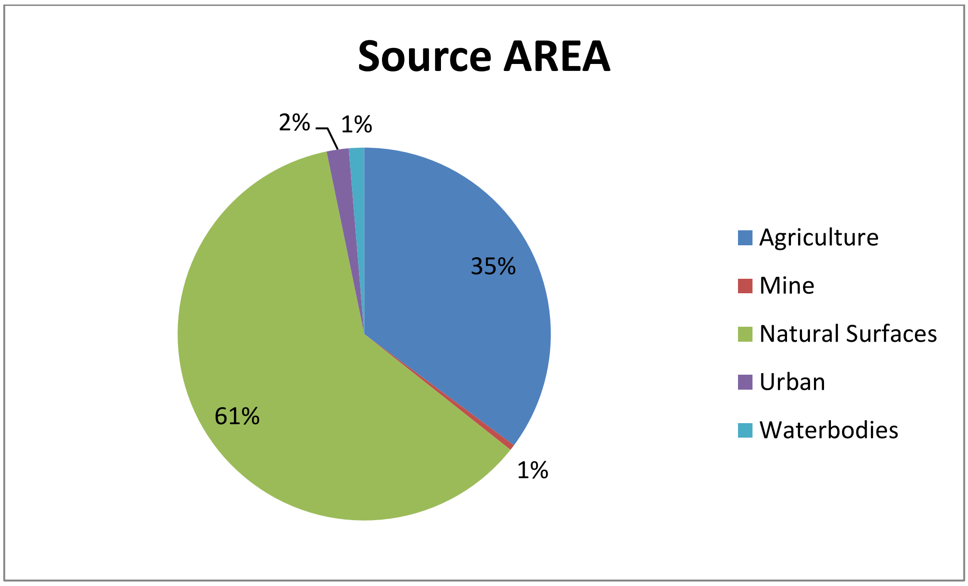


Figure 2.6b: Shows the distribution of major land use and land cover Classes in the dust source areas. (Refer to Appendix for Detail, TABLE A2.2). Source: NGI Data

2.5. DISCUSSION

2.5.1. Main emission areas for South Africa

The two provinces, Free State and North West have the greatest number of dust sources (figure 2.6a and 2.6b) and events that occurred between 2006 and 2016 in the MSG record. The Free State is centrally located and consists of grasslands and semi-arid vegetation and mountainous areas. The Western part of the Free State comprises of sandy soils (State of the Environmental Report, 2003). These soils are dry and windy conditions of the Free State enhance these soils to be blown. The North West Province. It is located in the Northern part of South Africa. The province is dominated by rural areas and like the in Free State agriculture is the main activity (Walmsley & Walmsley, 2002). It is not surprising to note that the Limpopo Province to be dust free because of its wet climatic conditions (Mzezewa *et al*., 2009), but as for the Eastern Cape, a great amount of land degradation occurs in the province such that it is easy to have an impression that the province would also suffer plenty of dust events (Le Roux, 2014). Despite those assumptions, results show that the Eastern Cape did not experience any major dust event during this period. It is also surprising that the driest Northern Cape is equally dust free given that it is the driest part of the country (South African Weather Service, 2003 and South Africa climate and weather, by region).

2.5.2. Main Soil Types in emission areas

Soils are never distributed randomly in any landscape. There are factors that influence the formation of soil such as climate, the parent rock, topography and biological factors. The Red –Yellow apedal soil (soils that have low clay continent) are the most predominant soils in the North West (Walmsley & Walmsley, 2002). The clay content of the North West varies greatly depending on the topography. There are number of few rocky regions that can be seen as well in the province. On the other hand, Free State comprises of high levels of Luvisols and Arenosols (figure 2.3b). Arenosols are known to be very sandy, like the North West soils because they develop from sand residual. They are popular in semi-arid regions where dry agriculture is practised (World reference base for soil resources, 2006). However, Luvisols are known to have very high clay content but only in the subsoil. This then becomes a disadvantage to the topsoil as it remains weak and prone to wind erosion. Again because of their fertile nature, Luvisols allow for a wide range of agricultural uses and their higher silt content causes them to be more susceptible when tilled or heavy machinery is used.

This suggests that soil types form part of the complex problem that South Africa is currently facing. If the same soil types, same land use and land cover conditions are found across South Africa, why is that only a certain part of the country is prone to frequent dust events? This suggests that further and even more detailed investigation is required because the two above components can only give little but not enough insight about these dust sources.

According to Wiggs & Holmes (2010), the Free State Province is characterised by environmental condition that allow dry commercial agriculture promoting wind erosion. Wiggs & Holmes (2010) continue to state that the amount of dust collected during their study shows that dust events tend to increase during the farming and windy season of the province. Both the Free State and North West exhibit characteristics that contribute significantly to the agriculture sector of South Africa. According to Botai *et al.* (2016) North West is the highest in producing cereal and oil seed whereas a widespread of dryland commercial agriculture is practiced in Free State. About 30% of the national maize production of South Africa is from the Free State (Wiggs & Holmes, 2010). Both these provinces rely heavily on agriculture though they are semi-arid regions. The South African government declared the two provinces drought disaster areas in 2015 and 2016. Both provinces are often hit by drought very hard (Botai, *et al.*, 2016). Grasslands are other significant features in the source area. However, at this point their contribution is unknown especially during drought cycles. Both Free State and North West display common soil structures and land uses, primarily agriculture. Soils with combination of high silt and sand continuation found in both provinces and heavy agricultural practises are all recipe for even more dust events.

The most dominant soil types in South Africa are the Luvisols, Arenosols, Cambisol and Leptosols (figure 2.3a and figure 2.3b). These soils are distributed widely across the country but interesting enough is to see that only those soils that are found in the source area are the most emissive. Why are the soils in the source area the most emissive? Can soil type alone determine the dust production in an area? What other controls contribute to dust production other than soil?

According to FAO soil group (2008), Leptosols are very susceptible to wind erosion. We see them distributed in provinces like the Eastern Cape, KwaZulu Natal and Northern Cape (figure 2.3a) but little to no dust events were recorded in theses provinces. Furthermore, Luvisols which contributed significantly to the dust events between 2006 and 2016 also extend to other parts of South Africa such as the South East part of the Northern Cape and the Northern parts of the Eastern Cape but very few dust events were recorded in these provinces. This suggest that dust emission causes cannot or do not rely on just one control. This is proven by the fact that the same soil type in the same country would not respond in the same manner to dust emission.

2.5.3. Landuse and Landcover in Emission areas

Figure 2.5a is a land use land cover map for South Africa which shows that it is mostly covered by natural surfaces as seen in figure 2.6a. 81% of the total surface in South Africa is natural surfaces followed by 13% of agriculture. Figure 2.6b shows the distribution of land use and land cover of the source area in percentages. 35% of the source areas are covered by agricultural, particularly commercial agriculture (Appendix Table A2.2) which is practised heavily in these parts of South Africa compared to any other parts of the country.

This is also shown by (Wiggs & Holmes, 2010) who states that the Free State provinces experiences a widespread of commercial dryland agriculture causing the area to be susceptible to dust events. The study also demonstrates that wind erosion did not occur mostly during the driest season of the area but rather during post-harvest season and the winter to summer transition a period when fields were fallow or crops too time to establish themselves.

Dust events are the result of different and dynamic conditions and controls and understanding them is important to ensure that other parts of South Africa are not affected as the source area in future. The source area and the rest of South Africa exhibit similar soil types, but we see soils respond differently towards wind erosion in different provinces of the country. However, the different land uses can be noted as well. There is a significant amount of dryland commercial agriculture performed in the source area. Studies (Wiggs & Holmes, 2010) and Botai *et al.*, 2006) show that the two provinces are the hub of agriculture in South Africa contributing significantly to wind erosion and dust events on the western most margin of rain fed agriculture prior to transitioning in the Karoo desert or drylands of the Northern Cape to the west.

To date South African dust research has mostly focused on mining dust, both above and underground (Nkosi, 2016; Wentzel, 2015). The mining sector is one of the most important sectors when it comes to the economy of South Africa. Adverse health and environmental attracted a lot of researchers (Wrigley, 1962; Finkelman, *et al.*, 2002) to the mining activities in South Africa. Wright (1962) states that the gold mine dumps and the tailings are the main source of air pollution in the Davidsonville, Krugersdorp and Kagiso areas in the Gauteng Province of South Africa. However, findings here show that none of the major dust events in the MSG record between 2006 and 2016 in South Africa are associated with major mining areas. Clearly the events that we see in MSG are major and the problems associated with mines are much more local in extend and impact.

Figure 2.6b shows that the major land use practice in the study area is agricultural. According to (Wiggs & Holmes, 2010) and (Hensley, *et al*., 2006), the agricultural land potential derived by the west-central and western Free State is classified as either very low potential or non-arable. Wiggs and Holmes, 2010 indicate that commercial drylands comprise 30% by area and about 57% is unimproved grasslands from the total area of 108 544 hectares that the study covered. Agricultural land use has changed in the many regions particularly in developing countries. South Africa has its economy, depending heavily on agriculture. Results show that most dust emanates from the commercial farming practice in South Africa. Though agricultural was a basic economic activity; using natural resources in harmony with the environment.

Agriculture represents a major industry worldwide (Tanrivermis and Bulbul, 2007). Agricultural activities can be considered a significant contributor to particulate emissions through tilling, harvesting and other activities associated with field preparation. Looking at the characteristics of the different soil types and the land use practices, Arenosols and the Luvisols have been noted as the most emissive soils in the source areas here. While these soils are very common throughout the region only in the FS and NW do we see dust being associated with these soil types. It appears that land use practices in particular promote emission here.

2.5.4. South Africa dust sources in regional and global context

In South Africa lakes and pans seem not to make any contribution to dust production as seen in neighbouring countries (Vickery *et al* 2013). Pans, ephemeral lakes and playas are some of the natural dust sources that have been identified throughout the world (Bullard and Livingstone, 2002; Mahowald *et al.*, 2013 and Bryant *et al.*, 2013) It is usually their sparsely vegetated surfaces and unconsolidated sediments that allow for dust activity. It is the ephemeral systems that are occasionally wet and dry up during some seasons that (Prospero, *et al.*, 2002) and (Washington, *et al.*, 2006) consider as the most important dust sources.

One of the persistent contributors of dust or mineral aerosols in the Southern hemisphere is Lake Eyre Basin (LEB) in Australia (Baddock, *et al.*, 2009) and (Tanaka & Chiba, 2006). LEB is the only inland dust source region in Australia and its geographic location prohibits an interaction with other dust sources in the continent. The several different environments cause the basin to be highly active when it comes to dust production (Baddock, *et al.*, 2009). The most noticeable similarity between Australia and South Africa is their climatic conditions which range from semi-arid to arid. It receives a mean annual rainfall of 125mm. According to Habeck-Fardy & Nanson (2014) Australia is becoming increasingly arid particularly the stony deserts of the LEB. Rivers and Lakes are active for very short periods of time and dry quickly increasing the sediment activity referred to by (Baddock, *et al.*, 2015).

Like the LEB, the major drivers of dust production in the Bodele Depression, Chad are strong erosive winds and highly erodible sediments. The dust plumes found in the Bodele Depression are said to come from shallow basins that have exposed diatomite (Washington, *et al.*, 2006). For dust emission to occur, regardless of the source there should be the availability of sediments. However, looking at the LEB and the Bodele Depression cases, there is a recognizable difference when compared to the case of South Africa.

The Makgadikgadi pan is one of the Southern Africa's most natural dust productive sources (Vickery, 2013. The pans are situated in Botswana and lie inside a draining basin. These pans are sandy and rarely have water. They have a dry, salty clay crust and the climate area is very arid (Vickery, 2014). Natural sources in South Africa such as pans, basins and lakes exist. However, dust activity was not recorded in these sources including the Northern Cape, where many dryland surfaces remain dust free according to the MSG record. The Etosha pan is also located in the semi-arid region of Namibia. The surface of the pan is underlined by silt, sand and clay (Bryant, 2003). Bryant discusses that the Etosha pan is not the sole dust source in the area but inundation that occurs in the pan plays a significant role.

It appears that the main emission areas in South Africa are anthropogenic sources where high levels of agriculture are practised. The major dust sources in the rest of Southern Africa are largely natural sources such as pans and basins. These natural structures are also present in South Africa, but it is clear to see that little to no dust is emitted from these sources in South Africa. Dust events recorded in South Africa were a result of commercial agriculture.

Results (Table A2.3) show that agricultural lands, more especially commercial agricultural lands are the major source of dust production in South Africa. South Africa shows no major natural dust sources as compared to other natural global dust sources and neighbouring dust sources. The Makgadikgadi pans in Botswana has been identified as the 9th most significant global dust source and the most significant dust source when it comes to Southern Africa (Vickery, 2010). Technically Makgadikgadi has many pans with sandy deserts very similar to the soils found in the Free State of South Africa, (Wiggs and Holmes, 2010) but the surfaces in Botswana are less emissive and emissions are restricted to the pans. The pans in the Northern Cape and other parts of SA don't seem to be important contributors, such that one can only speculate why this is, but in general appear to consist of hard clay which is different from Etosha and Makgadikgadi.

The American and Chinese (Shepherd *et al.,* 2016) dust bowls were an environmental catastrophe that occurred in America and China in the 1930s and in 1994 respectively. It is associated with massive soil erosion in the Great Plains (Hornbeck, 2012); (Baveye, *et al*., 2011). The American Dust Bowl is estimated to have substantially reduced agricultural land values. The dust bowl occurred because agricultural productivity expanded in the nineteenth century. Meanwhile, China suffered great soil loss and soil deterioration from overgrazing and overploughing.

These dust bowl stories seem to be very similar to the story of this study. The land use characteristics and surface characteristics are strikingly similar and difficult to ignore. The extensive use of the land for agricultural purposes was the ultimate reason that led to the American dustbowl. The Free State and the North West Province rely primarily on agriculture for their economic growth (Wiggs & Holmes, 2010). What we have been seeing in these parts of South Africa is the rising occurrence of dust events and the continuous use of the land which is not very different from what happened in Americas South Africa becoming a dustbowl? It is feasible that tillage and bare soil cause the soil to be more susceptible to wind erosion.

2.5.5. Natural and Anthropogenic dust sources.

Dust is emitted by different surfaces worldwide. Dust sources can be either natural (ephemeral lakes, basins and basins) or anthropogenic (agriculture and mines). Different dust source surfaces are influenced by different factors.

Table 2.1 below summarises some of the natural dust sources and anthropogenic dust sources discussed in this study. No natural sources were found in South Africa but only anthropogenic sources which a result of human induced activities such as agriculture mines and overgrazing. This is different to some of the Southern Africas other dust sources which tend to be natural sources. The South African situation at first glance resembles the American situation that resulted to the dustbowl in the 1930s.

Table 2. 1: Natural and anthropogenic dust sources of the world. Different sources contribute to dust emissions in different countries. Some are natural and some are human induced.

Countries	**Natural Sources**	**Anthropogenic Sources**
South Africa		Agriculture and Mines (Wiggs and Holmes 2010)
Botswana	Pans (Vickery, 2013)	
Namibia	Pans (Bryant, 2003)	
Chad	Dry lake (Washington *et al*, 2009)	
United States of America		Agriculture (Baveye,2011)
China		Agriculture (Hornebeck,2009)

3. SOIL PROPERTIES AND PARTICLE SIZE DISTRIBUTION

3.1. Introduction

In the previous chapter, we identified the soil types and land cover units responsible for South Africa's major dust emissions. In this chapter, we are continuing with a follow up of soil sampling and soil analysis. Dust emission is controlled by factors such as grain size, moisture, roughness and crust. However, this is a preliminary study that focuses only on the grain size characteristics of it. There are other studies that are currently focuses on the dynamic availability controls such as moisture are roughness.

3.1.1 Soil Sampling

The study area of interest was the North West Province and the Free State Province where 30 sites with various soil types were identified and sampled. The locations of the samples were marked using GPS and subsequently identified using the GIS methods. The sampling done for this study was not systematic but merely trying to provide an overview of the different soil types and land cover classes.

3.1.2 Grain Size Analysis

3.1.2.1. Sample Preparation

From the soil samples, fine to medium particles were chosen for laser diffraction. Before the samples were measured, they were taken to the laboratory where the larger lumps were crushed gently. The soil was sieved using a 2mm sieve. A quartering method is a systematic splitting process that can be performed on both dry and moist samples. Figure 3.1 below was used to obtain a homogenous soil sample. The process was performed on a flat plate on a flat surface.

Figure 3. 1: Quartering method. Soil samples were divided into four quarters to obtain a homogeneous soil sample of specific amount.

3.1.2.2. The Malvern Mastersizer 2000

The samples were sieved using a 2mm sieve. Three replicates from each sample were sieved using 2mm sieve. They were then suspended to a clear base, and in this case, it was water. The suspension was stirred and pumped into the measuring zone and introduced to the laser diffractometer. The results of the three replicates were later averaged giving standard results for each sample. All the samples were subjected to 180 ultrasonic dispersals ensuring full disaggregation of particles. The results are then displayed as particle size distribution. The data was exported to an excel program for further analysis and calculations. The size classes recorded by the Malvern were then summed into categories representing clay, silt and sand.

3.1.3. Cluster Analysis

R statistics is a programming language and software environment for statistical computing and graphics. The software is widely used by statisticians for developing statistical software data analysis programs (R Core Team, 2007). The R package comes with a wide variety of statistical and graphical techniques. These include linear and nonlinear modelling, classification, clustering and classical tests.

Because of the clustering technique that the software package comes with, R was used in this study for the purpose of clustering. According to R Core Team (2007), clustering is the grouping of items, objects, products or samples into different groups of similar characteristics. The characteristics could be one dimensional or can have many different dimensions. R provides many methods of clustering analysis such as hierarchical clustering, partitioning methods, fuzzy clustering, and density-based clustering and model-based clustering (R Core Team, 2007).

The hierarchical Agglomerative clustering (HAC) method was used in this study. This method was chosen because it reflects inter cluster similarities or dissimilarities. The data was organised by the cluster in a hierarchical order using the agglomerative approach. This means each sample is initially treated as a cluster of its own. As the analysis goes on, similar samples are combined forming a cluster. Eight clusters were chosen for this study. Eight clusters defined the results clearly compared to any other number. In hierarchical Agglomerative clustering dendrograms which are tree-like structures representing the hierarchical techniques were created. The same analysis can be seen in (von Holdt and Eckardt, 2017), where cluster analysis was conducted on soil samples based on two size categories, clay and silt. Similar to this study, von Holdt uses Ward's method of hierarchical tree clustering.

Figure 3.6 shows a dendrogram computed by Hierarchical agglomerative in R. When the programs run in R, each sample was assigned a numerical value, hence the values at the first level. These numeric values were later matched to their corresponding values. When clustering the soil samples, hierarchical clustering was used

3.1.4. Gradistat Analysis

Particle sizes and their distribution are important properties because they have great influence on properties such as susceptibility, transportation and deposition of sediments (Blott & Pye, 2001). Developed and published by Simon Blott, GRADISTAT is a particle size analysis software (Blott & Pye, 2001). Grain size analysis for individual samples and clusters for the study was performed using the widely available and free computer program (Blott and Pye, 2001; http://www.kpal.co.uk/gradistat.html). The computer program runs in Microsoft Excel and is best suited for calculating particle size statistics such as the mean, the mode and the kurtosis of both laser and granulometer data (Blott & Pye, 2001). Sediment fraction was calculated using gradistats and was categorised to different sizes (clay, silt and sand) (https://pubs.usgs.gov/ds/0850/downloads/metadata/grainsize_summary-statistics-met.htm). According to Quadros (2014), GRADISTAT is appropriate for analysing data that has been obtained from both sieve and laser diffractometer. The program requires the user to input the mass of the sample that was detected by the laser diffractometer (Blott & Pye, 2001). Each mass of each sample was put into its own bin in the program. GRADISTAT calculated different statistics for each sample. These statistics include mean, mode, standard deviation, skewness and the kurtosis. The program also gives graphical outputs for the samples analysed.

Moreover, the program classifies samples based on their physical description i.e. their textural group. The program looks at the sample as it calculates the sample statistics and names the sample according to its texture. For example, sand, very coarse sand, gravel or very fine silt

(Blott & Pye, 2001). GRADISTAT provides graphical outputs in terms of graphs showing grain size distribution and shows skewness, sorting and kurtosis of the grain size distribution. Because of the cluster analysis performed in this study and there were eight clusters in total, each cluster was put to GRADISTAT and treated as a single sample and this yielded descriptive statistics for each cluster.

3.2 Results: Soil Characteristics

3.2.1. Sample Location

The sampling of surface soils was done in both the Free State and North West Provinces of South Africa. According to the MSG results in the previous chapter, these provinces had the highest dust event occurrences compared to any other province in the country. Sampling framework was random and opportunistic, but an attempt was made to cover the spread of MSG sources and associated emission hotspots and to sample “typical” soils.

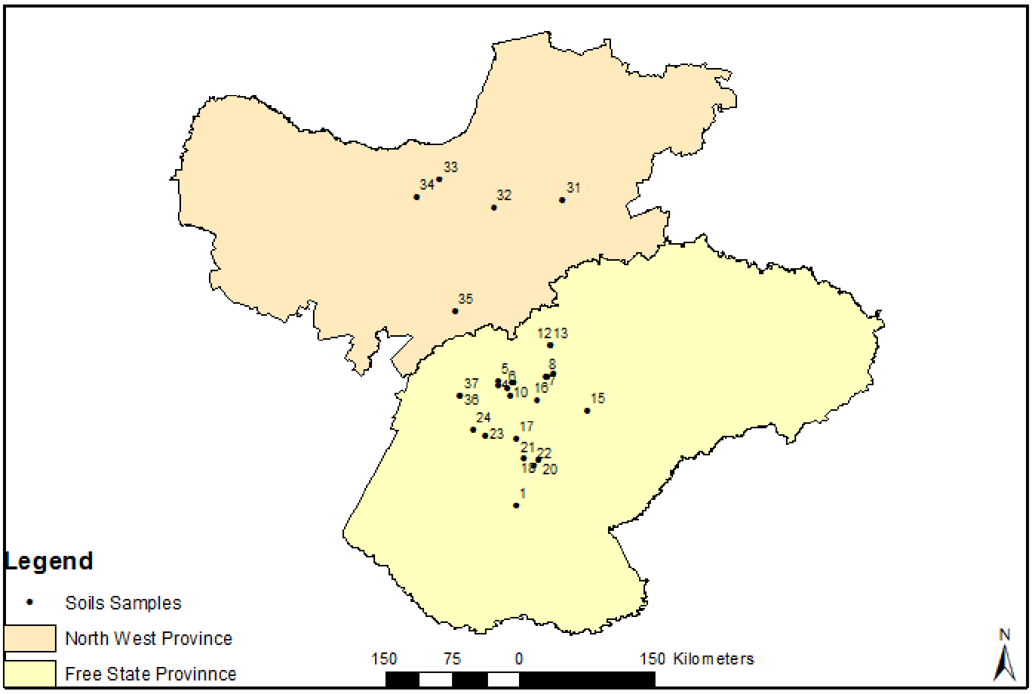


Figure 3. 2: Shows the location of the samples in the sampling sites (Free State and North West).

3.2.2. Grain Size

The particle size distribution and statistical data on the soil samples were extracted from the Malvern's computer. The data came in a form of an Excel spreadsheet. The data was plotted into graphs showing the particle size distribution for each graph. Results show distributions that are both unimodal and bimodal. The following graphs show the particle size distribution of each sample. There were thirty samples in total. Differences and similarities were noted among the samples with most samples having a higher percentage of silt and sand. A few samples were also noted for some fine material. The following diagrams show particle size distribution of each sample as represented by Malvern.

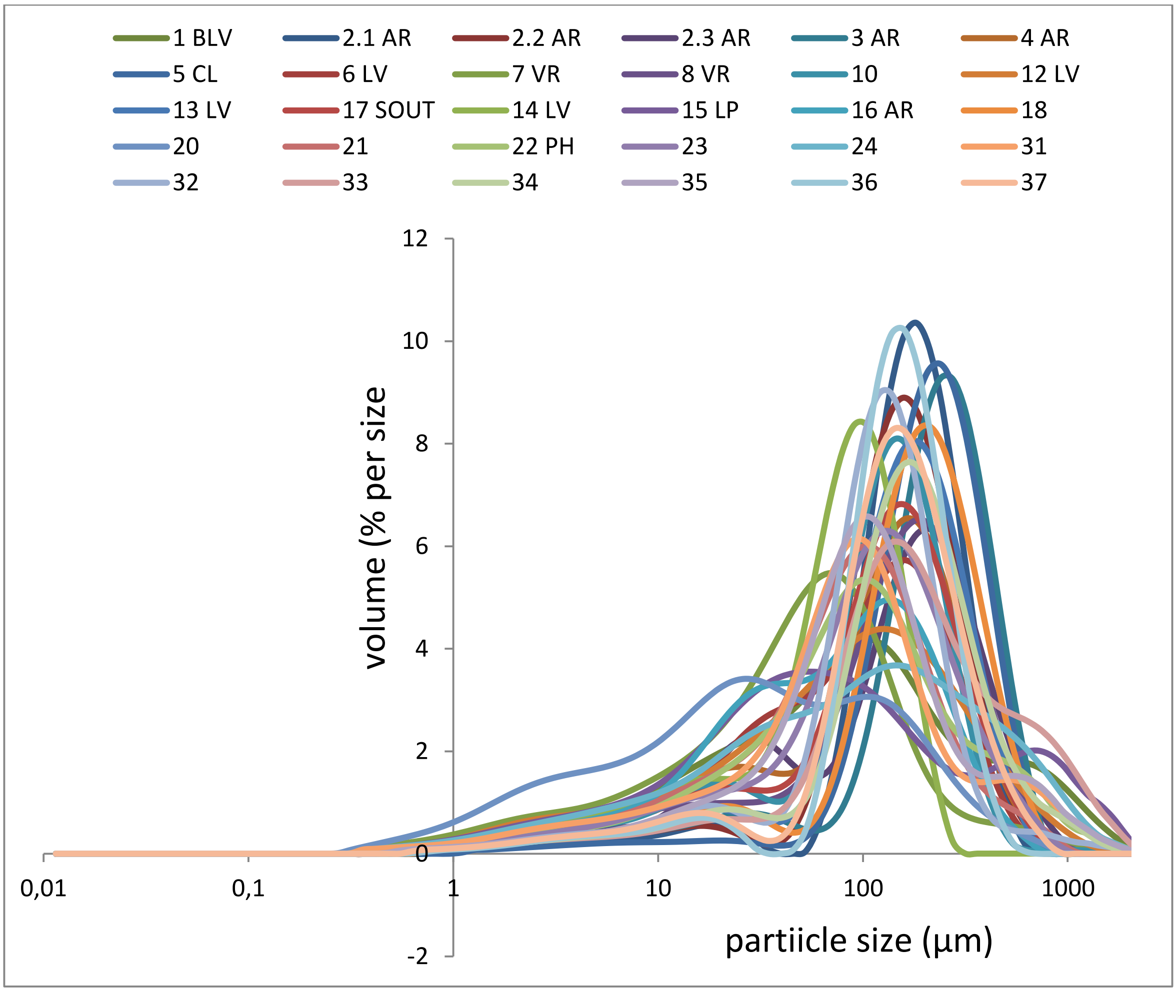


Figure 3. 3: Variation of particle size distribution of all the samples. The samples were sieved using a 2mm sieve. (Refer to appendix, table A3.2 for data).

3.2.3. Ranked soil texture

All the samples were then put to Gradistat to determine the textural composition of each sample. Texture (clay, silt and sand) play a very significant role when it comes to the dust production. The graph below shows that most of the soil samples are dominated by the silt and sand texture making them all likely to be emissive.

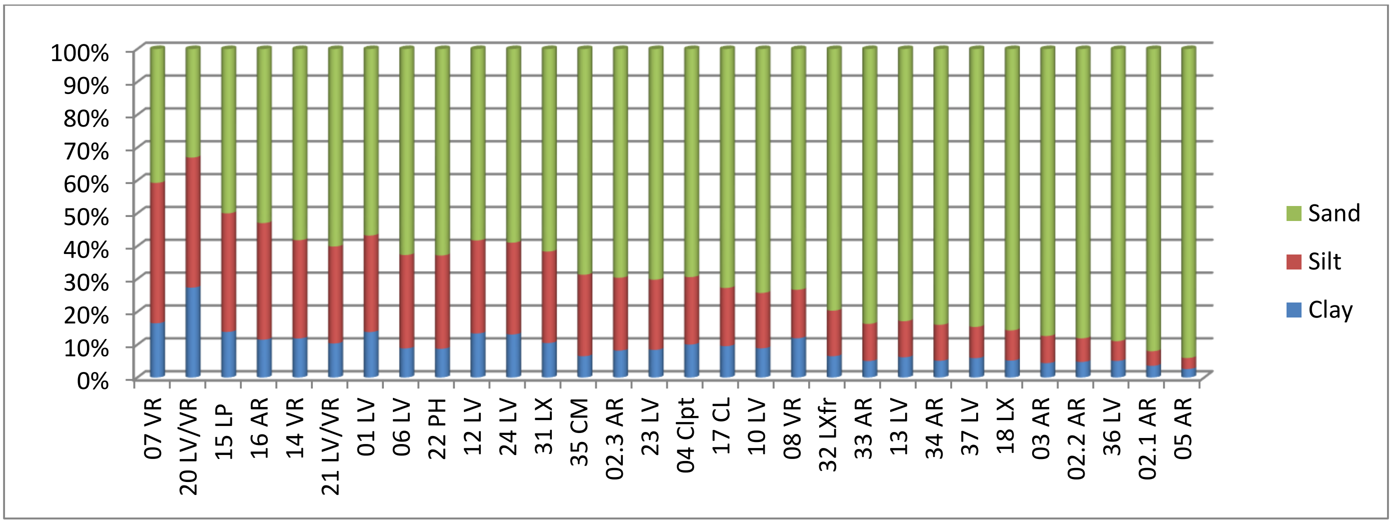


Figure 3. 4 Gradistat soil texture ranked. The above figure shows how each soil sampled was ranked by Gradistat according to texture from highest silt content to lowest. Most soil samples are dominated by the silt and sand content. (Refer to appendix A3.4 for details).

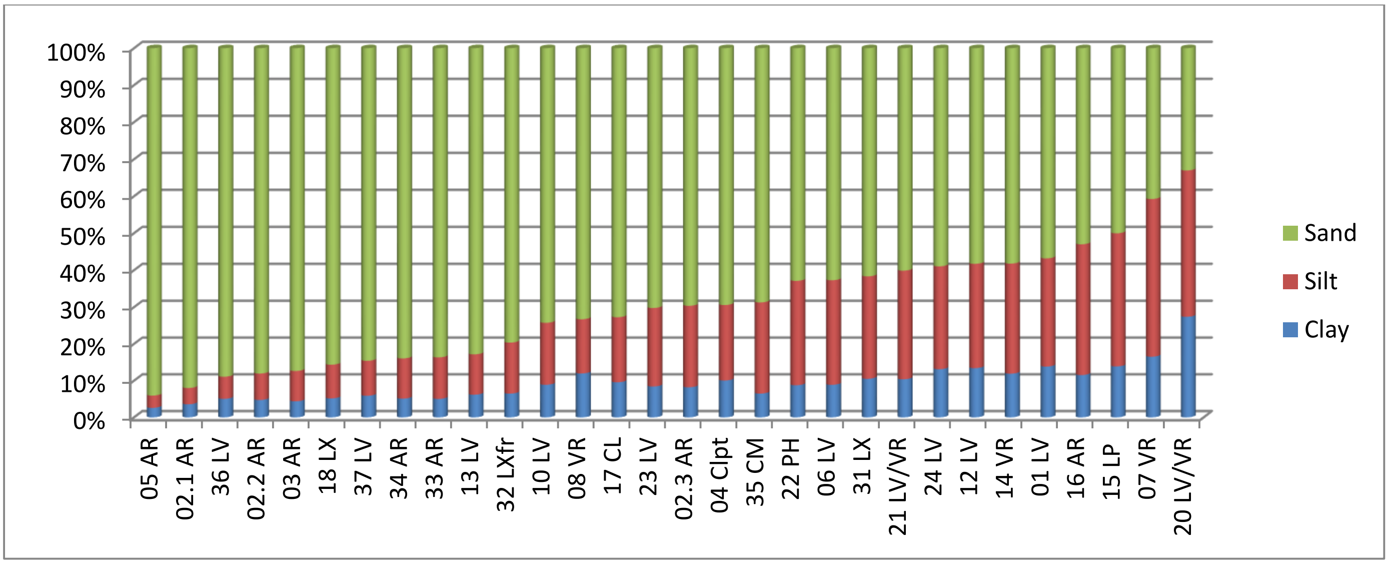


Figure 3. 5 Shows the texture of each soil sample. The above figure was ranked from highest sand to lowest sand. (Refer to appendix A3.4)

3.2.4. Cluster Statistics

A cluster dendrogram in R statistics is a result of grouping of soil samples that are more similar to each other. The similarity of these samples is based on their textural content. The dendrogram below shows how samples were grouped together to form the eight clusters.

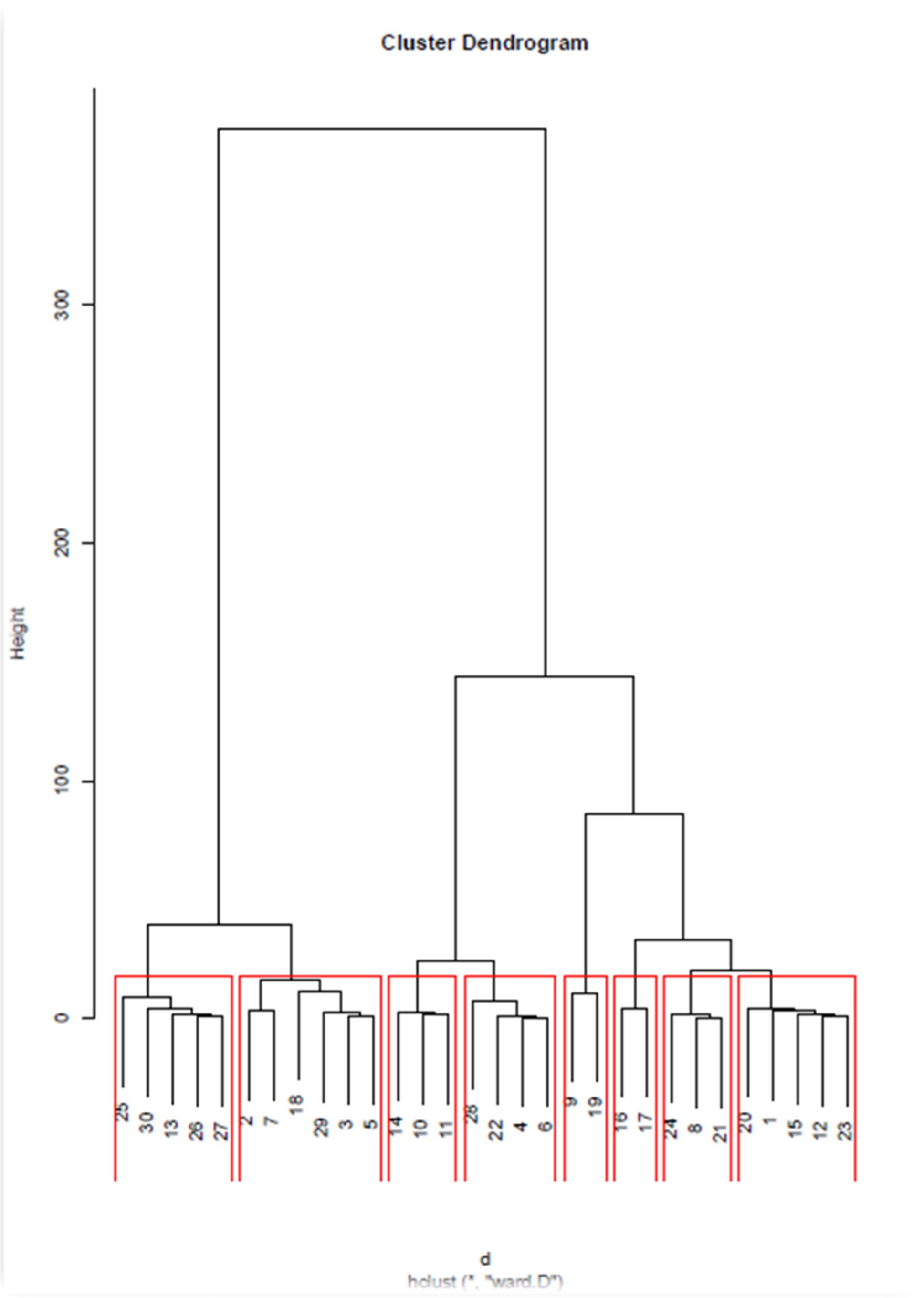


Figure 3. 6 The above figure shows the hierarchical dendrogram produced by R Statistics. Each sample was automatically assigned a number and clustered according to their textural similarities. The diagram has a total of eight clusters which are discussed in the following section.

The clusters were then located in a map. The map below (figure3.6) shows the clusters. Samples of the same clusters have the same colour. Figure 3.7 is a legend for figure 3.6 and also shows sample groupings.

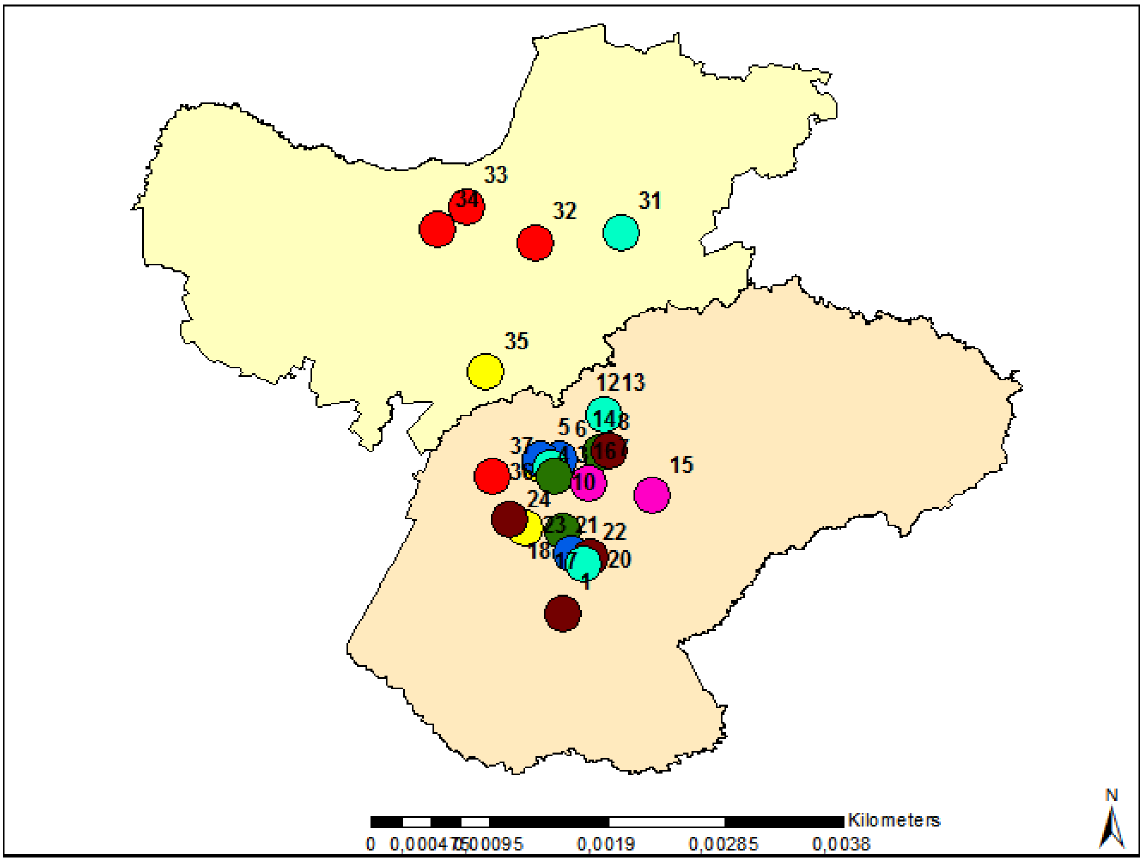


Figure 3. 7: Map of soil clusters. Samples of the same clusters are represented by the same colours.

Clusters	Samples					
🟥 1	37 LV	34 AR	33 AR	32 LX		
🟦 2	05 AR	2.1 AR	36 LV	2.2 AR	3 AR	18 LX
🟩 3	08 VR	19 LV	17 CL			
🟨 4	04 CL	23 LV	2.3 AR	35 CM		
🟧 5	20 LV	07 VR				
🟪 6	16 AR	15 LP				
🟦 7	13 LV	34 AR	22 PH	06 LV		
🟫 8	24 LV	12 LV	01 LV	21 VR	14 VR	

Table 3.1 Shows sample groupings and is a legend for figure 3.7.

3.3 Discussion

The section will attempt to discuss the third objective which seeks to understand the role played by grain size to dust production. The three soil textures (clay, sand and silt) will also be looked at in detail to examine how they might respond to wind, suspension and transport.

3.3.1. Dusty soils

The main reasons dust is emitted to the atmosphere are the strong erosive winds and the supply and availability of materials in semi-arid and arid regions (MacDougall, *et al*., 2012). Though wind is the main driver when it comes to wind erosion, surface characteristics such as sediment or particle distribution play a very important role.

Bullard *et al*. (2011) discuss how soil texture affects the erodibility of soil particles and the potential of sediments to generate dust. With the help of a Table 1.1 (Bullard *et al.,* 2011) shows that the mixture of both sand and silt that has both the high potential of being eroded and producing dust. In simple terms, sand alone, silt alone and clay on its own cannot produce dust. Table 3.3 shows the percentages of each cluster from silt, sand and clay.

Table 3.1 shows the texture percentage of each cluster. The textural groups range from very coarse sand to clay.

Clusters	Very coarse sand	Coarse sand	Medium sand	Fine sand	Very fine sand	Very coarse silt	Coarse silt	Medium silt	Fine Silt	Very fine silt	Clay
Cluster1	2	6	18	36	23	5	4	3	2	1	1
Cluster2	0	4	29	41	16	2	3	2	2	1	1
Cluster3	0	3	18	34	20	7	6	5	3	2	2
Cluster4	1	5	16	28	21	10	7	4	3	2	2
Cluster5	0	2	5	13	20	19	14	10	7	5	5
Cluster6	3	5	9	18	19	17	13	7	4	3	3
Cluster7	1	5	14	27	23	12	7	4	3	2	2
Cluster8	2	5	10	21	24	14	9	6	4	3	3

Particle size is one of the strongest and important parameters when it comes to the production of mineral aerosols. Therefore, grain size analysis can be used to provide important indicators into the nature of the sediments, their transport history and depositional conditions (Blott & Pye, 2001). When referring to surface controls other factors include dry soil and low sparse vegetation (Tegen & Lacis, 1996). The work that was conducted by (Tegen & Lacis, 1996) looked at particle sizes and they derived there three major soil textures, sand, silt and clay. They concluded that particle sizes <0.002mm (clay) have a tendency to stick and agglomerate to larger particles leading to a decrease of sediments to be susceptible to the wind.

The results from GRADISTAT about the clusters show that small percentages of clay were present in the clusters. Cluster 5 was the cluster with the highest percentage of clay (5.1%). However, this does not suggest that this cluster is any less effective when it comes to dust production. 9.5% of coarse silt and 18.9% of very coarse silt can be found in this cluster. Coarse material which is defined as material that is > 0.05mm mixed with the fine material (< 0.05mm) can lead to the breaking of the fine particles that are held together. Though larger particles settle faster as compared to finer particles, they have the ability to cause disaggregation. These larger particles act like "little bombs" to the very fine material disaggregating them into sizes that are susceptible to the wind. These particles may be suspended for a short period of time or longer periods depending on their sizes. (Marticorena, 2014), describes this process as dust released by the impact of saltating grains. Cluster 1 can also be another example of this process described by Marticorena (figure 3.5). The coarse material (sand 6.2%) can cause the fine material (fine sand 35.5%) to disaggregate leading to grains being suspended. The cluster contains two samples of Luvisols and a single sample of Lixisols. Though Luvisols and Lixisols are known to have high clay content leading to idea that the cluster could be less active when it comes to dust production because the very small grain size tends to stick together or agglomerate, according to the world base for soil resources (2006), the clay content found in Luvisols is mostly in the subsoil as compared to the topsoil. This is a result of the paedogenic processes such as clay migration.

However, (Desouza, *et al.*, 2015) shows that there was high dust flux found in Patiala, New Delhi and Kanpur because of the high clay content in the sand and silt loam soil types. According to (Marticorena, 2014) it is the fine particles that are emitted into the atmosphere as a result of wind erosion in semi-arid to arid regions. Marticorena describes soil roughness, soil moisture and size distribution as key role players of soil characteristics when it comes to the emission of dust because they control how frequent dust events are to occur in a particular area.

A total of 90% of sand is found in cluster 2. Over 40% of the sand is fine sand. The high percentage of sand is likely to lead to what is known as saltation which is defined by Marticorena (2014) as the horizontal movement of soil particles very close to the surface. As these particles rebound back to the surface, they have a very high potential to initiate the movement of other particles depending on what is on the surface.

Cluster 2 is not likely to be active when it comes to the production of dust because of the amount of sand present. Sand is made up of coarse materials. The saltation movement occurs on coarse material. Saltation is the horizontal movement of soil particles very close to the surface (Marticorena 2014). Because of their weight, these particles are never suspended to the atmosphere. According to (Tegen & Lacis, 1996), sand particles range between 2000µm and 50µm suggesting that some sand particles are finer than and some are coarse. Coarse materials have a short lifetime in the atmosphere as compared to the fine particles. They quickly settle down because of their weight (Marticorena 2014).

Because of these materials, the cluster is highly dominated by saltation. Though saltation is assumed to be dominant in the cluster, the 41, 1% of fine sand cannot be ignored. Shao, *et al*., 2011 highlight saltation as a prerequisite for dust emission. Fine sand has a great potential of being blown by the wind. It is the fine to the very fine sand that is assumed to cause sandstorms. Sandstorms are mostly dominated by sand. Because of the amount of sand (90%) found in the cluster, the cluster is more likely to produce more sandstorms or more active in sandstorms.

Figure 3. 8 Moderately Sorted Fine Sand Blown by wind. Figure 3.9 belongs to cluster 3.

Like cluster 2, cluster 3 has a high percentage of sand but some significant amount of silt can also be noticed. Marticorena, 2014 states that for dust particles to be easily eroded they must be in the range of 60-100µm. This is anything between silt and sand. With this in mind, it is also assumed that sufficient proportions of these soil textures must be present for the dust to be emitted. Cluster 1 and cluster 2 are both dominated by sand mostly. This suggests the high activity of saltation hence same conclusions drawn for cluster 2 are drawn for cluster 3. Similar to the many other clusters, cluster 4 has a recognisable amount of both clay and silt content. The combination of both these textures is the major causes of dust events as they are more likely to be suspended into the air. This makes this cluster one of the most emissive clusters.

Cluster 5 and cluster 6 were the finest clusters. Cluster 6 has 3% of very coarse sand. This Is a result of the soils contained in this cluster known as Leptosols, which are known to be extremely gravelly and stone making them in particular not emissive at all. However, availability of significant clay and silt is noted in this cluster hence it is one of the finest clusters. Availability of clay content and the fine to very fine silt particles suggests that agglomeration of the fine (clay) particles to the bigger particles (silt and very coarse sand) take place resulting to less or no particles to be eroded by the wind (Tegen, 1995).

The clay content indicates increased soil moisture. As the clay content increase so does the soil moisture. This is a result of the ability of clay minerals having the ability to absorb water in the interlayer positions. It is when the interlayer positions have reached their capacity when the water form interstitial water between the soil grains (Marticorena, 2014). This can lead to the development of capillarity forces. This partitioning of water in the soil can in rare instances lead to increased erosion but is highly dependent on the availability of soil suggests Fecan *et al* (1991). Consequently, soil moisture may be limited when it comes to areas that have dry and hot climatic conditions like the Free State and the North West.

3.3.2. The relationship between Soil types and dust in South Africa.

Soil types vary significantly depending on the amount of sand, silt and clay they contain. The availability of these variables strongly determines the ability of the surface to produce and emit dust *(*MacDougall*, et al.,* 2012*).* As discussed earlier, for dust to occur on any surface, both silt and sand material must be available. The following figure shows all the soil types that were samples in this study and the sand-silt ratio against soil type.

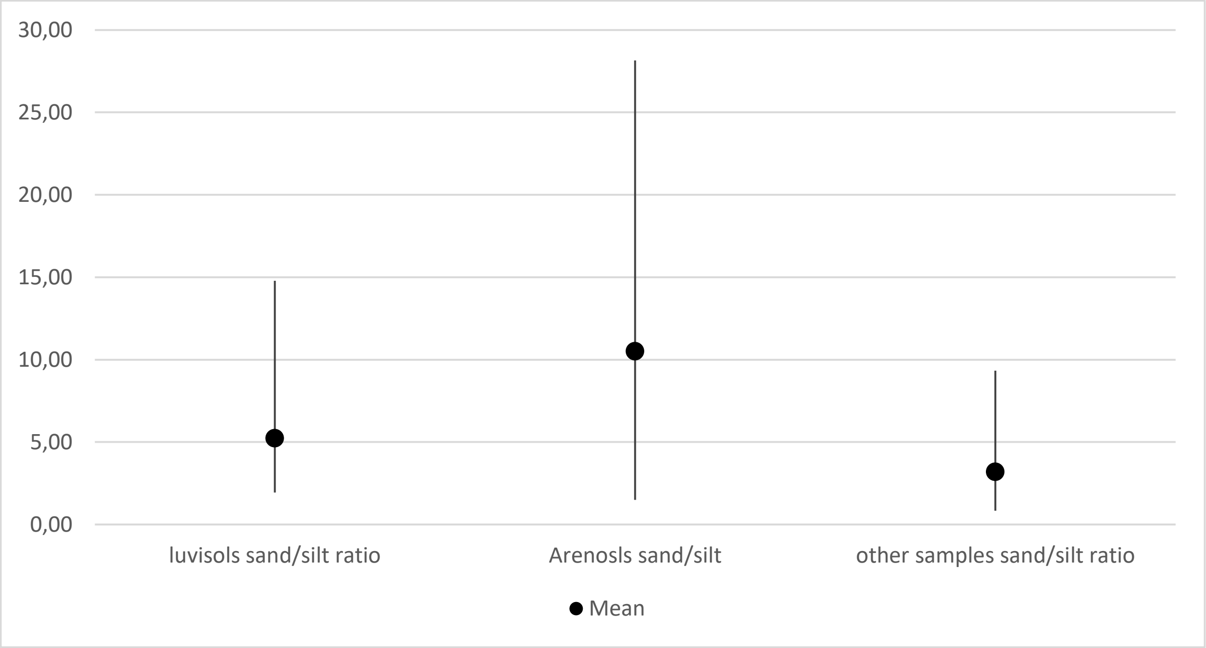


Figure 3. 9 silt and sand variation from all the soils sampled Arenosols and Luvisols for the study. (Data in the Appendix (A3.4))

Presence of both the sand and silt can be noted in all of the soil types, but a significant amount is seen in Arenosols and Luvisols. Though these soil types are known to be the highly emissive, *(Hartemink & Huting, 2008)* and *(Van Wambeke, 1992)*, this does not exclude the rest of the soils. Because soil materials can be blown from one surface to another by wind, surfaces of the same field are likely to influence each other causing a lot of variation in the same field.

This shows that one cannot rely entirely on soil type and to understand the surface controls of dust production, however soil maps can be used as a starting point, but one needs to be careful of the amount of generalization. The same field with the same features can vary a lot when it comes to the movement of soil particles. The process of sampling and analysing the sampling into detail allows for researchers to make a more accurate decision about the sample at that time.

Cluster 2 with over 40% of fine sand was found to be a very interesting cluster. The cluster is also dominated by Arenosols (soils with more than 70% of sand and less than 15% of clay). These are soils that are comprised mostly of sand which explains the high percentage of sand found in this cluster. Although Arenosols are known to have coarse texture resulting in them being high permeable with low water and nutrient holding capacity, they are very easy to cultivate. Their coarse texture makes it possible for them to be used for agricultural purposes in various ways. However (Van Wambeke, 1992) states that though Arenosols do not have suitable or favourable attributes for farming, in Southern Africa their extensive use for arable farming is increasing because of the growing population. Arenosols in semi-arid and arid regions (like the Free State and North West Provinces of South Africa) are usually used for dry farming purposes and grazing (World Reference Base for Soil Resources, 2006).

Figure 3. 10: Shows cultivated Arenosols East of Bultfontein Free State

3.3.3. The relationship between Land cover and Dust

Wind erosion and susceptible agricultural fields promoted by anthropogenic activities are major problems resulting in the emission of dust in South Africa (Wiggs & Holmes, 2010).

Figure 3.12 shows the silt sand ratio between Arenosols and Luvisols in cultivated land and in grasslands and the rest of the soil types clumped together between two different land covers. There is a great difference in ratio that can be noticed in cultivated lands as compared to the grasslands. Minimum production of dust can be expected from grasslands as they are covered. According to (Wiggs and Holmes, 2010), the Free State province has sandy soils (Arenosols and Luvisols) that support heavy farming of dry land and cultivation. Wiggs and Holmes conclude that the above activities are the cause of dust production in the Free State and the grasslands are mostly on the receiving end.

Because Arenosols and Luvisols are dominant and are highly active in dust production, it is their coarse texture that makes it possible for them to be used for agricultural purposes in various ways. Luvisols in cluster 1 and most dominant in cluster 8 are known to have very high clay content which makes them completely different from Arenosols in terms of clay content but more similar to soils like Lixisols. This would highly suggest that they are less emissive when it comes to dust emissions or are resistant to wind erosion as the fine materials of clay would indicate that the soil particles agglomerate, but unfortunately that is not the case. The clay content of these soils is found in the subsoil mostly and less in the topsoil. This is a result of pedogenic processes such as clay migration.

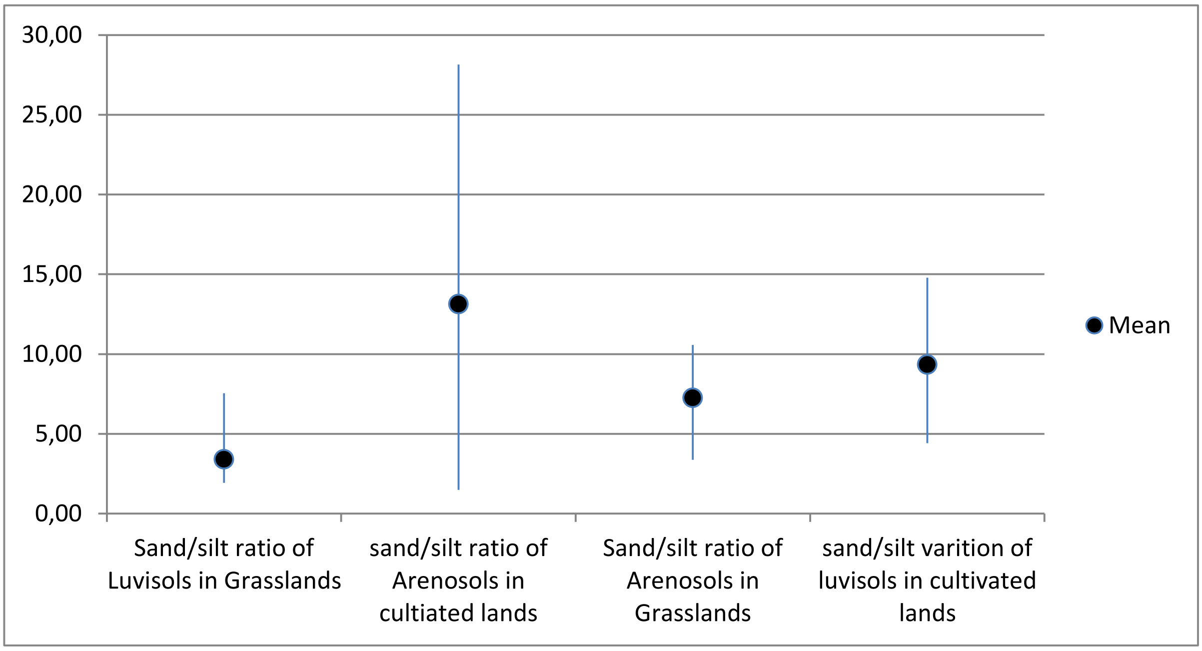


Figure 3. 11 *Silt-Sand ratio of different land use and land cover and soil types. Cultivated Arenosols were recognised to be the most emissive surfaces. 3.3.5. Comparison of surface characteristics to other known sources in Southern Africa*

Southern Africa has some of the major sources contributing to dust at a regional scale (Vickery, 2013). The Kalahari Dunes, Makgadikgadi and Kuiseb silts are some of the known sources. The following pyramid was designed to compare the sand and silt ratios of South Africa to those known sources. The pyramid (figure 3.18) shows that Kuiseb silts comprise of silt material mostly as the name would suggest. As stated earlier, it is the combination of both sand and silt that is required for the dust to occur. These Kuiseb silts are very different from the many soils of South Africa in that sand is largely absent from the texture. However the proximity to mobile sand dunes is critical in mobilising these silts and may be responsible for this major source. The Makgadikgadi pan sediments are more similar to the South African soil surfaces which are represented by the small black dots in the pyramid. Both the pans and South African soils fall between the silt and sand category. According to Vickery (2014), the relatively fine materials and sediments found in the Makgadikgadi result to the pans being a significant source of dust emission similar to most South African sediments. The addition of fine sand and resulting sand silt mixture is making this source particularly emissive. The Kalahari and Namib dunes have sandy sediments making them different to the South African sediments. These are unlikely to be major sources given the lack of fine sediment. While South African soils have a mixture of sand and silt, the Kuiseb Silts may not have enough sand to produce dust and the dunes may not have enough silt to supply dust.

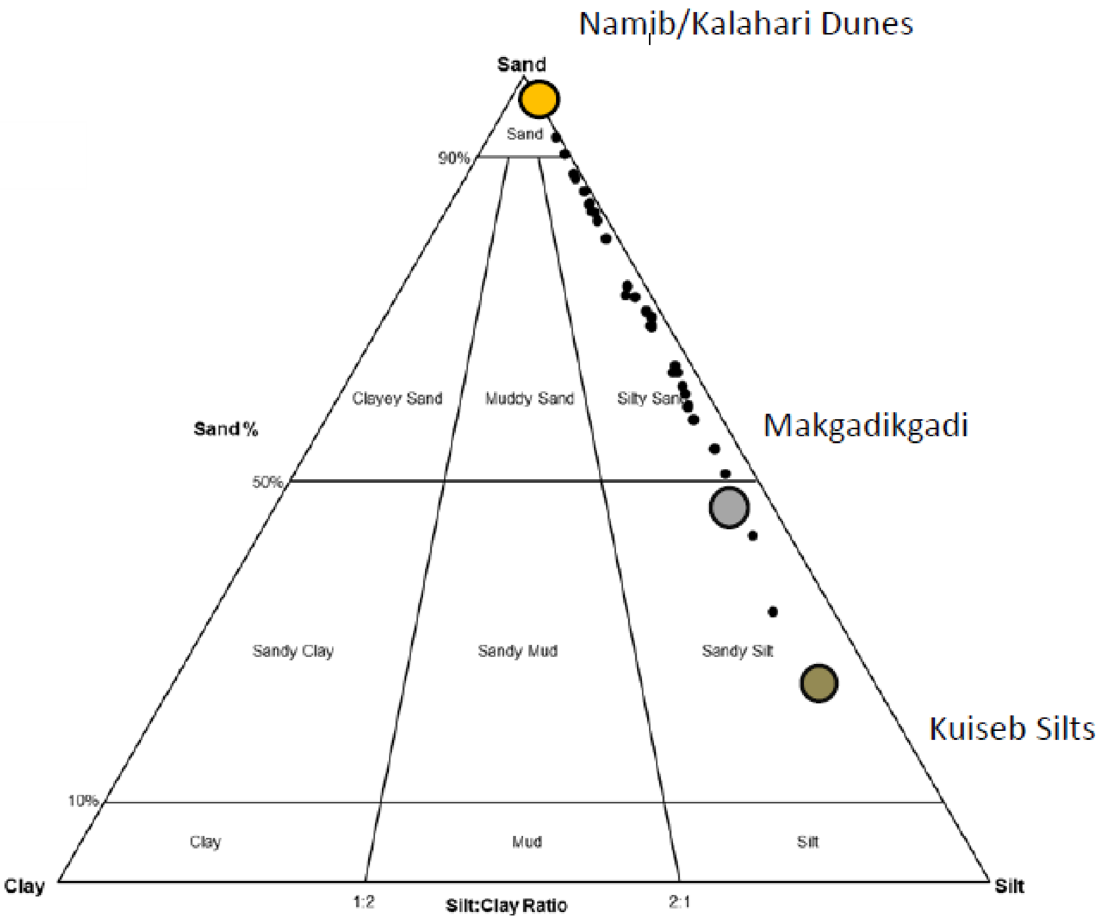


Figure 3. 12 The pyramid shows the sand and silt ratio of other known sources in Southern Africa. The sediments are compared to the South African sediments represented by the small black dots which have an ideal fine sand and coarse sand texture needed for dust production.

3.3.4. Conclusion

Particle size distribution plays an important role in dust generation and dust emission. Different textures influence the dust process such as surface creep of very large materials, saltation of sandy sediments and suspension of finer materials. Larger materials have a short lifetime in the atmosphere compared to the smaller materials. Results indicate that for dust emission to occur both silt and sand material must be available. This is also shown by many studies (e.g. Vickery (2014)).

Most of the clusters in the study show a combination of these sediments making most of the culprits of dust production in South Africa. Similar sediments can be seen in the Makgadikgadi Pans. What is interesting is that the Makgadikgadi pans are natural sources whereas the South African sources are mostly activated by anthropogenic factors particularly commercial agriculture both have the ideal sand/silt mixture as indicated by Bullard *et al*. (2011).

4. CONCLUSION AND RECOMMENDATIONS

4.1. Introduction

The chapter presents the summary, conclusion and recommendations on dust sources in South Africa. These recommendations emerge from the results and findings of the study. Different techniques and methods were used to see this study to completion. Both GIS and lab work techniques (PSD) were vital for this study. Relationships between the two methods were established and it was clearly noted that dust production depends heavily on the particle size distribution of the soil when compares to and other soil components. However, factors such as and land cover and land use cannot be ignored as they contribute significantly to soil tillage and loosening of particles.

Dust production process is a natural phenomenon and has been happening since the beginning of time. However, it is difficult to ignore that in the most recent years the process has been occurring at an accelerated rate due to human interference causing imbalances to the natural rate.

4.2. Conclusion

South Africa has many mining activities located all over the country, especially the Gauteng province (Wentzel, 2008) but no unusual dust can be seen in those areas, at least in the MSG Satellite data. The main sources of large dust emissions in South Africa, according to the MSG record are agricultural areas in the central Free State Province and the western edge of commercial agriculture. Most of the Free State dust can be attributed to land use, grazing and permanent removal of topsoil for agricultural purposes (Holmes *et al.*,2012). The results of this study are similar to those of Mahasa (2015) where it is stated that amongst the variables investigated for soil erosion by wind in the province, they all pointed to one commonality which was the Mid-western portion of the Free State. Having said that, it is possible that some of the mines may contribute to the plumes and it is also possible that grasslands and some pans especially during drought season also play a role in the dust production.

On the other hand, soil types, namely Arenosols and Luvisols are not unique to the dustiest Free State Province. These soils are widespread across the country. However, no emissions can be seen in many other parts of South Africa. They also extend deep to the dry Kalahari where no contemporary plumes or emissions are seen. However, it has been said that potential future drought might increase dust emissions in the Kalahari (Bhattachan *et al*., 2012 and Thomas *et al.*, 2005). It is conceivable that what is seen in the Free State is the beginning of what might occur elsewhere in the region. This is indicative of the fact that the soil type component is not a giveaway to detect dust emission in a particular area but how the land of a particular area is used is of great importance.

Grain size analysis reveals that texture with sand silt ratios is knowingly responsible for dust in many other places. Such is noted in (Bullard, *et al*., 2011; Marticorena, 2014). These studies indicate that different textures of soil undergo different processes such as creeping, saltation and suspension. The process of each particle is determined by the many forces that act upon a particle such as size which was investigated in this study. (Marticorena, 2014) states that particles smooth surfaces with dry sandy and silty soils have low erosion threshold making them probable to frequent dust emissions. This can also be seen in (Bullard, *et al*., 2011) where different surfaces and their ability to emit dust. Bullard concludes that sand silt surfaces such as ephemeral lakes and dry unconsolidated lakes have high dust generation potential. Most of the soil samples sampled and analysed in this study were composed of mostly sand and silt material though these soils are different soil types. This is indicative of the fact highlighted earlier that there is no uniqueness that can be placed to soil types but controls in the soil type play a major role in dust production and dust emission. It can be concluded that the susceptibility of soil particles in the atmosphere is highest in the central Free State in South

Africa where commercial agriculture is practised extensively. Mahasa (2015) adds that human activities in the area are more likely to blame as they accelerate the rate of erosion in the area. Land use plays a major role in South African dust emission surfaces. This study has provided a combination of elements and components on the surface controls of dust emission in South Africa. These components show that the study area will continue to be susceptible to wind erosion and dust events unless proper land use and land management structures are put in place to mitigate the problem. The continuous intense use of land because of the growing demand agricultural products puts a lot of pressure on the soil escalating the wind erosion process. The study indicates that at least where commercial agriculture is practiced; the soil is more vulnerable to dust emission. Poor maintenance and the rising improper land use perpetuated by anthropogenic activities may continue to lead to significant deterioration of what were once well-developed grasslands. Though the study area is a semi-arid region (Wiggs & Holmes, 2010) the widespread practice of agriculture, especially commercial agriculture is practised.

4.3. Recommendations

Recommendations resulting from this study would be the use of GIS, remote sensing, and particle size distribution software to determine other parts of South Africa susceptible to local airborne dust emission below the detection of MSG and to identify dust events on a broader national scale (e.g. a survey of the entire country) using other surface or satellite. This should be followed by detailed studies of all the components that are involved in dust production such particle size distribution, land use, soil moisture and land cover change (LULCC) and soil carbon to help determine more areas that need to be investigated.

The understanding of dust emission processes involves many significant steps. However, as mentioned earlier, this study focuses entirely on a single control. The knowledge of all of the controls could provide guidance in further understanding dust sources together with their classification (Bullard, *et al*., 2011). There is further need for understanding the other dynamic aspects of dust emissions such as wind, moisture, roughness and crust in order to make precise conclusions about dust emission in South Africa.

This study has characterising South Africa’s Major Dust Sources using MSG image record which established rain-fed agricultural areas on Arenosols and Luvisols as the primary dust sources in the image record.

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APPENDICES

APPENDIX 1: From data chapter 2

a) Summary of the Methods section

The study is a follows a multidisciplinary approach where two data chapters are used. It relies on both primary and secondary data. Primary data involves soil sampling in the site and secondary data involves the use of MSG data (Eckardt, unpublished), soil maps and land use and land cover maps.

The first data chapter of the study makes use of the secondary data to locate the MSG point data in the South Africa. It was noticed that most of the points fall on the Free State and on the North West Province of South Africa as seen in figure 2.2a. The African soil map was also used to identify the types and forms of soils present in the source area. Different soil types were noticed in the source area, however, it was noticed that most of the MSG points fall on the Luvisols and Arenosols (figure 2.3a). Land cover and land use map (NGI layer) was used to identify land use activities that are found in the source area. South Africa is mostly covered by natural surfaces (figure 2.6a). However, a huge percentage of agricultural activities is noted in the source area (figure 2.6b). It was concluded that agriculture contributes significantly in dust production.

The second data chapter involved soil sampling and grain size analysis. There were 30 sites with various soil types that were identified in this study. The locations of the samples were marked using GPS and subsequently identified using the GIS methods. The sampling done for this study was not systematic but merely trying to provide an overview of the different soil types and land cover classes. Grain size analysis involved sample preparation is required. The soil samples were sieved using a 2mm sieve and a quartering method was used for splitting the soil sample in a systematic manner. The soil was suspended into water in the Malvern. The results from the Malvern were put to R statistics where eight randomly chosen clusters were created. R statistics arranged the sample into clusters based on their textures. Samples of similar textures were put on the same cluster.

Table A2.1: MSG Dust Source Record for South Africa (Eckardt unpublished). The unpublished records were used to produce chapter 2 results for this study.

Lon	Lat	State
26,19	-28,17	FS
26,75	-28,17	FS
26,62	-27,86	FS
26,92	-28,33	FS
25,52	-27,75	FS
26,22	-29,02	FS
25,53	-27,72	FS
26,86	-28,28	FS
25,73	-27,98	FS
26,18	-28,14	FS
26,55	-28,01	FS
26,68	-27,75	FS
26,29	-29,12	FS
28,71	-27,88	FS
27,31	-28,00	FS
26,98	-28,13	FS
26,02	-28,47	FS
20,07	-26,84	NC
26,80	-28,41	FS
25,97	-28,07	FS
25,58	-26,99	NW
28,20	-26,29	GP
28,11	-26,63	GP
25,93	-28,20	FS
26,54	-28,62	FS
27,00	-28,44	FS
25,99	-28,34	FS
26,59	-28,83	FS
26,80	-28,38	FS
26,34	-29,33	FS
26,03	-29,59	FS
25,24	-26,09	NW
25,50	-26,81	NW
20,15	-25,08	NC
20,46	-25,24	NC

26,03	-28,03	FS
26,54	-27,92	FS
26,98	-28,17	FS
24,54	-27,80	NW
25,18	-26,36	NW
26,99	-28,43	FS
27,55	-28,18	FS
28,02	-28,43	FS
26,72	-28,01	FS
26,31	-28,35	FS
26,08	-28,60	FS
25,91	-28,33	FS
26,80	-28,20	FS
20,16	-26,91	NC
25,62	-28,65	FS
26,48	-28,43	FS
26,27	-28,43	FS
26,78	-28,68	FS
26,05	-27,76	FS
25,67	-27,93	FS
29,61	-26,68	MP
29,61	-27,22	MP
29,49	-27,76	FS
26,50	-29,04	FS
27,28	-28,88	FS
29,21	-28,37	FS
26,61	-29,74	FS
25,43	-26,92	NW
26,11	-26,93	NW
26,76	-28,66	FS
26,24	-29,25	FS
26,26	-28,22	FS
26,94	-28,76	FS
25,74	-27,29	NW
25,87	-26,33	NW
26,39	-26,59	NW
26,35	-27,05	NW
25,07	-26,71	NW
25,50	-27,31	NW
26,22	-28,38	FS
26,63	-28,76	FS
26,10	-29,11	FS
25,93	-26,65	NW
25,67	-28,68	FS

26,09	-28,55	FS
26,47	-27,79	FS
25,92	-29,16	FS
25,78	-28,75	FS
22,01	-27,01	NC
25,42	-26,53	NW
26,13	-29,05	FS
26,14	-29,39	FS
26,16	-29,17	FS
25,77	-29,19	FS
26,25	-28,97	FS
25,57	-26,90	NW
26,18	-29,13	FS
26,01	-29,26	FS
25,39	-28,29	FS
26,47	-28,61	FS
26,22	-29,07	FS
26,70	-28,13	FS
29,72	-25,50	MP
26,13	-28,91	FS
25,87	-27,74	FS
26,22	-28,63	FS
25,50	-27,14	NW
25,99	-27,70	FS
25,69	-28,82	FS
25,75	-27,53	NW
26,31	-28,90	FS
30,18	-26,17	MP
25,54	-26,61	NW
25,26	-25,97	NW
25,73	-27,01	NW
21,72	-27,15	NC
26,35	-27,97	FS
26,02	-28,35	FS
24,82	-26,06	NW
25,97	-27,65	FS
25,47	-27,85	FS
26,04	-28,15	FS
25,98	-28,07	FS
26,70	-27,74	FS
25,45	-27,86	FS
25,79	-28,86	FS
26,04	-29,19	FS
26,42	-28,11	FS

28,83	-27,94	FS
27,05	-28,19	FS
26,36	-29,16	FS
28,95	-28,14	FS
27,84	-27,64	FS
29,36	-27,22	MP
26,17	-28,89	FS
26,25	-30,19	FS
26,51	-26,26	NW
26,40	-28,15	FS
19,53	-30,41	NC
20,01	-29,98	NC
19,82	-32,50	WC
26,78	-28,28	FS
25,36	-26,12	NW
25,91	-26,14	NW
26,37	-27,64	FS
27,36	-27,11	FS
28,91	-28,02	FS
26,16	-28,30	FS
26,75	-28,16	FS
24,88	-26,04	NW
25,32	-26,02	NW
25,83	-26,40	NW
25,36	-27,46	NW
25,67	-28,11	FS
26,42	-27,80	FS
25,13	-26,76	NW
25,43	-27,64	NW
25,41	-28,30	FS
26,51	-27,92	FS
25,99	-28,27	FS
26,05	-28,07	FS
26,83	-28,48	FS
26,41	-27,85	FS
25,75	-28,22	FS
26,56	-28,25	FS
26,01	-28,12	FS
26,34	-27,81	FS
26,38	-29,39	FS
26,18	-28,09	FS
26,59	-27,86	FS
27,23	-27,77	FS
26,80	-28,42	FS

26,72	-27,81	FS
25,88	-27,11	NW
26,38	-27,83	FS
27,20	-27,41	FS
24,26	-28,19	NC
23,65	-28,89	NC
23,37	-29,43	NC
23,89	-29,67	NC
26,45	-29,07	FS
26,36	-28,49	FS
25,89	-29,45	FS

Table A2.2: The following table shows the total area covered by each class and the 10km MSG buffer extracted from the map and the percentage of dust produced by each class. All numbers are pixel counts. This data was used to determine the percentages of land use and land cover in South Africa.

NGI Class	SA Total	Dust 10km	Percentage
Water seasonal	699666	23409	3
Water permanent	20256837	111554	1
Wetlands	10303156	377145	4
Indigenous Forest	4341657	14739	0
Thicket /Dense bush	83281061	442748	1
Woodlan/Open bush	121878093	982889	1
Grassland	259793459	13744840	5
Shrubland fynbos	55354565	4046	0
Low shrubland	374967690	8485329	2
Cultivated comm fields (high)	17481684	427720	2
Cultivated comm fields (med)	25138658	2170968	9
Cultivated comm fields (low)	59156924	10328860	17
Cultivated comm pivots (high)	4051964	188717	5
Cultivated comm pivots (med)	1622680	103173	6
Cultivated comm pivots (low)	1938291	159528	8
Cultivated orchards (high)	2103237	1445	0
Cultivated orchards (med)	843113	2890	0
Cultivated orchards (low)	440759	2601	1
Cultivated vines (high)	1222905	0	0
Cultivated vines (med)	598688	0	0
Cultivated vines (low)	129078	0	0
Cultivated permanent pineapple	90414	0	0
Cultivated subsistence (high)	3254240	2601	0
Cultivated subsistence (med)	8855485	20808	0
Cultivated subsistence (low)	8393671	220218	3

Cultivated cane pivot - crop	146297	0	0
Cultivated cane pivot - fallow	33509	0	0
Cultivated cane commercial - crop	3354197	0	0
Cultivated cane commercial - fallow	797100	0	0
Cultivated cane emerging - crop	305891	0	0
Cultivated cane emerging - fallow	94337	0	0
Plantations / Woodlots mature	15716227	130628	1
Plantation / Woodlots young	1303514	7803	1
Plantation / Woodlots clearfelled	1642918	1445	0
Mines 1 bare	1872705	78897	4
Mines 2 semi-bare	1246757	99994	8
Mines water seasonal	19801	867	4
Mines water permanent	80827	7803	10
Mine buildings	55100	3179	6
Erosion (donga)	2179874	37570	2
Bare none vegetated	130404312	1447312	1
Urban commercial	523403	31501	6
Urban industrial	559501	37570	7
Urban informal (dense trees / bush)	105527	867	1
Urban informal (open trees / bush)	70003	1734	2
Urban informal (low veg / grass)	365199	17629	5
Urban informal (bare)	52891	2023	4
Urban residential (dense trees / bush)	1979916	97104	5
Urban residential (open trees / bush)	207571	7225	3
Urban residential (low veg / grass)	831076	23409	3
Urban residential (bare)	80053	4046	5
Urban school and sports ground	314504	17918	6
Urban smallholding (dense trees / bush)	481254	24565	5
Urban smallholding (open trees / bush)	457061	8959	2
Urban smallholding (low veg / grass)	1415454	221663	16
Urban smallholding (bare)	14226	2023	14
Urban sports and golf (dense tree / bush)	224489	5491	2
Urban sports and golf (open tree / bush)	52411	578	1
Urban sports and golf (low veg / grass)	175115	6647	4
Urban sports and golf (bare)	8451	0	0
Urban township (dense trees / bush)	275862	4624	2
Urban township (open trees / bush)	213305	6936	3
Urban township (low veg / grass)	1144214	58089	5

Urban township (bare)	304248	44217	15
Urban village (dense trees / bush)	3748921	0	0
Urban village (open trees / bush)	2550694	2890	0
Urban village (low veg / grass)	11909474	85833	1
Urban village (bare)	100999	578	1
Urban built-up (dense trees / bush)	188466	1734	1
Urban built-up (open trees / bush)	120564	1156	1
Urban built-up (low veg / grass)	322069	7803	2
Urban built-up (bare)	271887	15606	6
Total	1254520149	40372144	3

Table A2.3: shows all the agricultural activities in South Africa and the area covered by the 10km buffer

Class 1 (Agriculture)	SA Total	Dust 10km	Percentage
Cultivated comm fields (high)	17481684	427720	2,4
Cultivated comm fields (med)	25138658	2170968	8,6
Cultivated comm fields (low)	59156924	10328860	17,4
Cultivated comm pivots (high)	4051964	188717	4,7
Cultivated comm pivots (med)	1622680	103173	6,4
Cultivated comm pivots (low)	1938291	159528	8,2
Cultivated orchards (high)	2103237	1445	0,1
Cultivated orchards (med)	843113	2890	0,3
Cultivated orchards (low)	440759	2601	0,6
Cultivated vines (high)	1222905	0	0
Cultivated vines (med)	598688	0	0
Cultivated vines (low)	129078	0	0
Cultivated permanent pineapple	90414	0	0
Cultivated subsistence (high)	3254240	2601	0,1
Cultivated subsistence (med)	8855485	20808	0,2
Cultivated subsistence (low)	8393671	220218	2,6
Cultivated cane pivot - crop	146297	0	0
Cultivated cane pivot - fallow	33509	0	0
Cultivated cane commercial - crop	3354197	0	0
Cultivated cane commercial - fallow	797100	0	0

Cultivated cane emerging - crop	305891	0	0
Cultivated cane emerging - fallow	94337	0	0
Total (Agriculture)	140053122	13629529	9,7

Table A2.4: The table shows the total area covered by mines in South Africa and the ones covered by the 10km buffer.

Class 2 (Mines)	SA Total	Dust 10km	Percentage
Mines 1 bare	1872705	78897	4,2
Mines 2 semi-bare	1246757	99994	8,0
Mines water seasonal	19801	867	4,4
Mines water permanent	80827	7803	9,7
Mine buildings	55100	3179	5,8
Total (Mines)	3275190	190740	5,8

Table A2.5: The table shows the total area covered by Natural surfaces in South Africa and the ones covered by the 10km buffer.

Class 3 (Natural Surfaces)	SA Total	Dust 10km	Percentage
Indigenous Forest	4341657	14739	0,3
Thicket /Dense bush	83281061	442748	0,5
Woodland/Open bush	121878093	982889	0,8
Grassland	259793459	13744840	5,3
Shrubland fynbos	55354565	4046	0
Low shrubland	374967690	8485329	2,3
Total (Natural Surfaces)	899616525	23674591	2,6

Table A2.6: Table 2.4 shows the total surface covered by Plantation

Class 4 (Plantation)	SA Total	Dust 10km	Percentage
Plantations / Woodlots mature	15716227	130628	0,8
Plantation / Woodlots young	1303514	7803	0,6
Plantation / Woodlots clearfelled	1642918	1445	0,1
Total (plantation)	18662659		0,7

Table A2.7: Shows the water bodies

Class 5 (Waterbodies)	SA Total	Dust 10km	Percentage
Water seasonal	699666	23409	3,3
Water permanent	20256837	111554	0,6
Wetlands	10303156	377145	3,7
Total (Waterbodies)	31259659	512108	1.6

Table 2.8 shows the built and Urban environment in South Africa

APPENDIX 2 from data chapter 2: A3

a) *Geocoded Sampled images*

Geocoded images of sampled points (later areas) were taken. The images (figure A3a) were put to Google photos where the coordinates were derived. The XY coordinates from Google photos were put to an excel document. Once the coordinates were recorded, they were plotted in ArcMap 10.3.1. This was done to locate the samples in the South Africa.

The Spatial Join Tool in Arc Map was used. An **event layer** was created matching the **X-field** to the **longitudes** and the **Y-field** to the **latitudes** and the **Z field** remained as **NONE**. After creating an event layer the spatial Join tool between the new shapefile and existing shapefiles were created to locate the sampled points.

Class 6 (Urban)	SA Total	Dust 10km	Percentage
Urban school and sports ground	314504	17918	6,0
Urban smallholding (dense trees / bush)	481254	24565	6,7
Urban smallholding (open trees / bush)	457061	8959	0,8
Urban smallholding (low veg / grass)	1415454	221663	2,5
Urban smallholding (bare)	14226	2023	4,8
Urban sports and golf (dense tree / bush)	224489	5491	3,8
Urban sports and golf (open tree / bush)	52411	578	4,9
Urban sports and golf (low veg / grass)	175115	6647	3,5
Urban sports and golf (bare)	8451	0	2,8
Urban township (dense trees / bush)	275862	4624	5,1
Urban township (open trees / bush)	213305	6936	5,7
Urban township (low veg / grass)	1144214	58089	5,1
Urban township (bare)	304248	44217	2,0
Urban village (dense trees / bush)	3748921	0	0
Urban village (open trees / bush)	2550694	2890	14,2
Urban village (low veg / grass)	11909474	85833	2,4
Urban village (bare)	100999	578	1,1
Urban built-up (dense trees / bush)	188466	1734	3,8
Urban built-up (open trees / bush)	120564	1156	15,7
Urban built-up (low veg / grass)	322069	7803	1,7
Urban built-up (bare)	271887	15606	3,3
Urban residential (bare)	80053	4046	5,1
Urban commercial	523403	31501	14,5
Urban industrial	559501	37570	2,4
Urban informal (dense trees / bush)	105527	867	0,7
Urban informal (open trees / bush)	70003	1734	0,6
Urban informal (low veg / grass)	365199	17629	0,9
Urban informal (bare)	52891	2023	1,0
Urban residential (dense trees / bush)	1979916	97104	0,9
Urban residential (open trees / bush)	207571	7225	5,7
Total (Urban)	29068808	23409	2,5










Figure A3.1: the above figures show the areas that were sampled in Free State and in the North West Province of South Africa

Table A3.1 Soil Samples from the Free State and NW Province

Sample ID	Provinces	Road	Cover	Soil Map	Lat	Lon	Photo ID
01 LV	Free State	N1	Grassland	LVha	-29,395	26,096	5757
02.1 AR	Free State	700	Cultivated	ARfl	-28,172	26,048	5759
02.2 AR	Free State	700	Cultivated	ARfl	-28,159	26,065	5759
02.3 AR	Free State	700	Cultivated	ARfl	-28,159	26,065	5759
03 AR	Free State	700	Grassland	ARfl	-28,159	26,065	5775
04 Clpt	Free State	708	Grassland	ARfl	-28,194	25,915	5793
05 AR	Free State	708	Cultivated	ARfl	-28,152	25,915	5795
06 LV	Free State	708	Grassland	LVcr	-28,222	25,999	5805
07 VR	Free State	710	Riparian	VRcc	-28,101	26,4	5809
08 VR	Free State	710	Cultivated	VRcc	-28,103	26,397	5814
10 LV	Free State	708	Cultivated	LVcr	-28,292	26,031	5824
12 LV	Free State	719	Small Vlei	LVfr	-27,794	26,432	5731
13 LV	Free State	719	Grassland	LVfr	-27,794	26,432	5733
14 VR	Free State	710	Cultivated	VRcc	-28,083	26,47	5868
15 LP	Free State	708	Hill	LPli	-28,449	26,81	5874
16 AR	Free State	708	Cultivated	ARfl	-28,347	26,306	5877
17 CL	Free State	700	Pan Margin	CLpt	-28,731	26,095	5882
18 LX	Free State	700	Cultivated	LXha	-28,923	26,169	5889
20 LV/VR	Free State	30	Riparian	LVcc/VR	-28,943	26,32	5903
21 LV/VR	Free State	30	Riparian	LVcc/VR	-28,943	26,32	5905
22 PH	Free State	N 1	Grassland	PHha	-28,998	26,268	5908
23 LV	Free State	64	Grassland	LVcc	-28,703	25,788	5932
24 LV	Free State	64	Grassland	LVcc	-28,643	25,663	5933
31 LX	Free State	14	Grassland	LXha	-26,327	26,562	5978
32 LXfr	North West	14	Grassland	LXfr	-26,406	25,872	5980
33 AR	North West	375	Grassland	ARha/CM	-26,121	25,322	5982
34 AR	North West	18	Grassland	ARfl/CM	-26,306	25,09	5985
35 CM	North West	34	Grassland	CMcr	-27,455	25,479	5987
36 LV	North West	59	Cultivated	LVfr	-28,299	25,531	5988
37 LV	North West	59	Cultivated	LVfr	-28,299	25,531	5990

Table A3.2: Soil Texture Obtained from Malvern Size Classes

Sample ID	Clay	Silt	Sand	<2	2to10	10to63	63to100	100to1000	>1000
01 LV	14	29	57	3,5	10,3	29,4	11,6	42,1	3,0
02.1 AR	4	4	92	0,5	3,1	4,4	8,1	83,9	0,0
02.2 AR	5	7	88	0,9	3,8	7,2	12,5	75,6	0,0
02.3 AR	8	22	70	2,1	6,1	22,2	6,4	63,2	0,1
03 AR	4	8	87	0,7	3,7	8,3	3,0	84,4	0,0
04 Clpt	10	21	69	2,1	8,0	20,6	9,9	59,2	0,3
05 AR	3	3	94	0,4	2,2	3,3	5,5	88,6	0,0
06 LV	9	28	63	2,1	6,7	28,4	11,7	50,7	0,3
07 VR	17	43	41	4,4	12,1	42,7	16,0	24,6	0,2
08 VR	12	15	73	3,0	8,9	14,8	9,4	63,8	0,1
10 LV	9	17	74	2,1	6,7	16,9	13,0	61,1	0,2
12 LV	13	28	58	3,3	10,1	28,3	11,8	45,8	0,7
13 LV	6	11	83	1,2	5,0	11,0	10,2	72,7	0,0
14 VR	12	30	58	2,7	9,2	29,9	23,1	35,1	0,0
15 LP	14	36	50	3,3	10,6	36,1	10,3	35,0	4,7
16 AR	12	36	53	2,9	8,6	35,5	12,1	40,9	0,0
17 CL	10	18	73	2,0	7,5	17,7	11,8	60,9	0,0
18 LX	5	9	86	0,9	4,2	9,2	6,6	79,1	0,0
20 LV/VR	27	40	33	7,4	20,0	39,6	8,9	24,1	0,0
21 LV/VR	10	30	60	2,5	7,9	29,5	16,5	43,6	0,0
22 PH	9	28	63	2,0	6,8	28,4	14,9	46,5	1,5
23 LV	8	21	70	1,6	6,8	21,4	14,5	55,7	0,0
24 LV	13	28	59	3,2	10,0	27,9	9,4	47,5	2,0
31 LX	10	28	62	2,6	7,9	27,9	17,4	42,7	1,6
32 LXfr	6	14	80	1,4	5,1	13,9	17,4	61,5	0,8
33 AR	5	11	84	1,2	3,9	11,3	11,2	67,9	4,6
34 AR	5	11	84	1,0	4,1	11,0	10,0	72,7	1,3
35 CM	6	25	69	1,4	5,1	24,8	17,6	49,3	1,7
36 LV	5	6	89	0,8	4,2	6,0	13,0	75,9	0,0
37 LV	6	10	85	1,1	4,8	9,5	13,4	71,2	0,0

Table A3.3: Soil Texture Obtained from Gradisdat

Sample ID	V F GR	V C SA	C SA	M SA	F SA	V F SA	V C SI	C SI	M SI	F SI	V F SI	CLAY
01 LV	0	4	9	10	17	19	14	10	7	4	3	3
02.1 AR	0	0	2	26	48	17	1	3	2	1	1	0
02.2 AR	0	0	3	21	42	23	3	2	2	2	1	1
02.3 AR	0	0	7	23	28	12	10	9	4	3	2	2
03 AR	0	0	9	39	33	7	3	4	2	2	1	1
04 Clpt	0	0	3	18	31	18	8	8	5	3	2	2
05 AR	0	0	7	38	39	11	1	1	1	1	1	0
06 LV	0	0	2	15	27	21	14	9	5	3	2	2
07 VR	0	0	2	4	13	26	22	13	8	5	4	4
08 VR	0	0	5	22	31	17	6	5	5	4	3	3
10 LV	0	0	1	14	37	23	6	7	5	3	2	2
12 LV	0	1	6	14	21	20	14	9	6	4	3	3
13 LV	0	0	3	24	38	19	4	4	3	2	2	1
14 VR	0	0	0	1	24	38	15	7	6	4	3	2
15 LP	0	6	10	8	12	17	17	13	7	4	3	3
16 AR	0	0	1	11	23	21	17	13	6	4	3	3
17 CL	0	0	3	18	32	21	7	6	5	3	2	2
18 LX	0	0	6	30	37	13	3	4	3	2	1	1
20 LV/VR	0	0	2	6	13	15	16	16	11	8	7	6
21 LV/VR	0	0	3	9	24	27	15	8	5	3	2	2
22 PH	0	2	7	11	21	25	15	8	5	3	2	2
23 LV	0	0	4	15	29	25	11	6	5	3	2	1
24 LV	0	3	10	15	18	16	13	10	6	4	3	3
31 LX	0	2	6	8	20	29	15	7	5	3	3	2
32 LXfr	0	1	2	10	38	30	6	4	3	2	2	1
33 AR	0	6	13	18	29	20	5	3	2	2	1	1
34 AR	0	2	7	22	36	18	4	4	3	2	1	1
35 CM	0	2	7	9	24	29	14	6	4	2	1	1
36 LV	0	0	1	18	47	25	1	3	3	2	1	1
37 LV	0	0	4	20	39	24	3	3	3	2	1	1

Table 3.3a explains the abbreviations in table 3.3

VF GR	Very fine gravel
VC SA	Very coarse sand
CSA	Coarse sand
MSA	Medium sand
FSA	Fine sand
VFSA	Very fine sand

VCSI	Very coarse silt
CSI	Coarse silt
MSI	Medium silt
FSI	Fine silt
VFSI	Very fine silt

Table A3.4 shows the data of figure 3.3

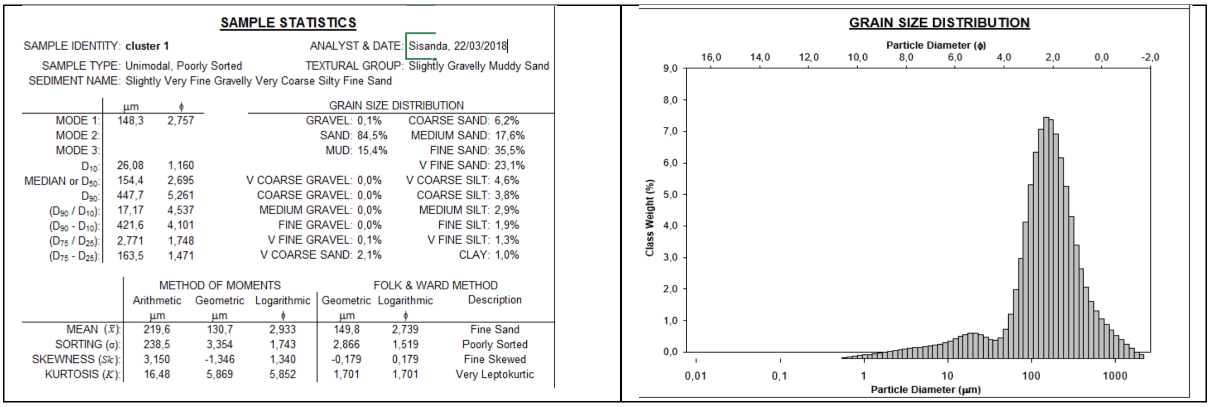
	Sand/silt ratio of Luvisols in Grasslands	sand/silt ratio of Arenosols in cultiated lands	Sand/silt ratio of Arenosols in Grasslands	sand/silt varition of Luvisols in cultivated lands
Mean	3,41	13,14	7,25	9,36
Minimum	1,93	1,49	3,38	4,40
Maximum	7,54	28,15	10,57	14,78

Table A3.5 shows the data of figure 3.4

	Luvisols sand/silt ratio	Arenosls sand/silt	other samples sand/silt ratio
Mean	5.24	10,52	3,21
Minimum	1,93	1,49	0.83
Maximum	19,78	28,15	9,33

Cluster information of the different clusters in section **3.2.3**. Percentages of different soil textures can be seen. On the right of every sample statistics information of every cluster is the grain size distribution of every cluster.

Cluster 1 -4



SAMPLE STATISTICS

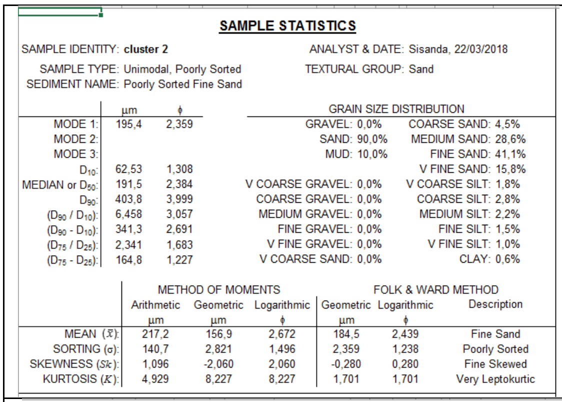
SAMPLE IDENTITY: **cluster 1**
ANALYST & DATE: Sisanda, 22/03/2018
SAMPLE TYPE: Unimodal, Poorly Sorted
TEXTURAL GROUP: Slightly Gravelly Muddy Sand
SEDIMENT NAME: Slightly Very Fine Gravelly Very Coarse Silty Fine Sand

	μm	ϕ
MODE 1:	148,3	2,757
MODE 2:		
MODE 3:		
D_{10}:	26,08	1,160
MEDIAN or D_{50}:	154,4	2,695
D_{90}:	447,7	5,261
(D_{90} / D_{10}):	17,17	4,537
$(D_{90} - D_{10})$:	421,6	4,101
(D_{75} / D_{25}):	2,771	1,748
$(D_{75} - D_{25})$:	163,5	1,471

GRAIN SIZE DISTRIBUTION

GRAVEL:	0,1%	COARSE SAND:	6,2%
SAND:	84,5%	MEDIUM SAND:	17,6%
MUD:	15,4%	FINE SAND:	35,5%
		V FINE SAND:	23,1%
V COARSE GRAVEL:	0,0%	V COARSE SILT:	4,6%
COARSE GRAVEL:	0,0%	COARSE SILT:	3,8%
MEDIUM GRAVEL:	0,0%	MEDIUM SILT:	2,9%
FINE GRAVEL:	0,0%	FINE SILT:	1,9%
V FINE GRAVEL:	0,1%	V FINE SILT:	1,3%
V COARSE SAND:	2,1%	CLAY:	1,0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic ϕ	Geometric μm	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	219,6	130,7	2,933	149,8	2,739	Fine Sand
SORTING (σ):	238,5	3,354	1,743	2,866	1,519	Poorly Sorted
SKEWNESS (Sk):	3,150	-1,346	1,340	-0,179	0,179	Fine Skewed
KURTOSIS (K):	16,48	5,869	5,852	1,701	1,701	Very Leptokurtic



SAMPLE STATISTICS

SAMPLE IDENTITY: **cluster 2** ANALYST & DATE: Sisanda, 22/03/2018

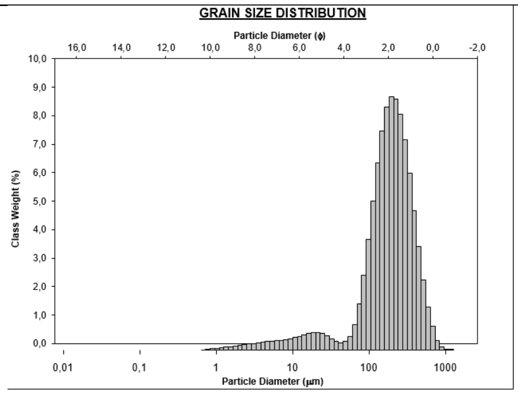
SAMPLE TYPE: Unimodal, Poorly Sorted TEXTURAL GROUP: Sand
SEDIMENT NAME: Poorly Sorted Fine Sand

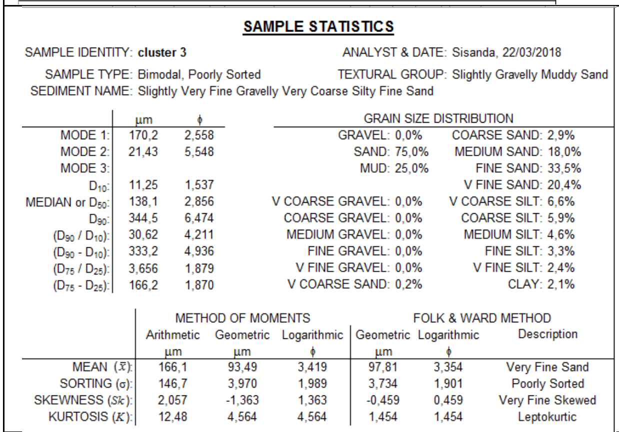
	µm	ϕ
MODE 1:	195,4	2,359
MODE 2:		
MODE 3:		
D_{10}:	62,53	1,308
MEDIAN or D_{50}:	191,5	2,384
D_{90}:	403,8	3,999
(D_{90} / D_{10}):	6,458	3,057
$(D_{90} - D_{10})$:	341,3	2,691
(D_{75} / D_{25}):	2,341	1,683
$(D_{75} - D_{25})$:	164,8	1,227

GRAIN SIZE DISTRIBUTION

GRAVEL:	0,0%	COARSE SAND:	4,5%
SAND:	90,0%	MEDIUM SAND:	28,6%
MUD:	10,0%	FINE SAND:	41,1%
		V FINE SAND:	15,8%
V COARSE GRAVEL:	0,0%	V COARSE SILT:	1,8%
COARSE GRAVEL:	0,0%	COARSE SILT:	2,8%
MEDIUM GRAVEL:	0,0%	MEDIUM SILT:	2,2%
FINE GRAVEL:	0,0%	FINE SILT:	1,5%
V FINE GRAVEL:	0,0%	V FINE SILT:	1,0%
V COARSE SAND:	0,0%	CLAY:	0,6%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic	Geometric	Logarithmic	Geometric	Logarithmic	Description
	µm	µm	ϕ	µm	ϕ	
MEAN ($\bar{x}$):	217,2	156,9	2,672	184,5	2,439	Fine Sand
SORTING (σ):	140,7	2,821	1,496	2,359	1,238	Poorly Sorted
SKEWNESS (Sk):	1,096	-2,060	2,060	-0,280	0,280	Fine Skewed
KURTOSIS (K):	4,929	8,227	8,227	1,701	1,701	Very Leptokurtic





SAMPLE STATISTICS

SAMPLE IDENTITY: **cluster 3** ANALYST & DATE: Sisanda, 22/03/2018

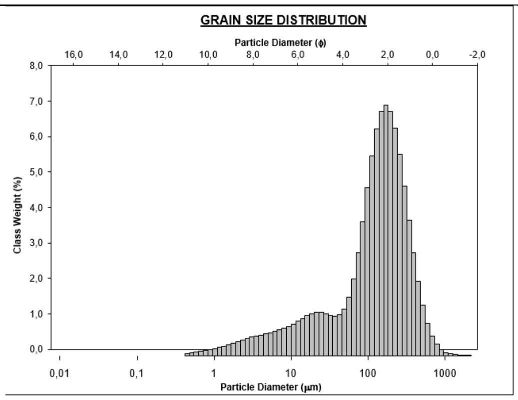
SAMPLE TYPE: Bimodal, Poorly Sorted TEXTURAL GROUP: Slightly Gravelly Muddy Sand
SEDIMENT NAME: Slightly Very Fine Gravelly Very Coarse Silty Fine Sand

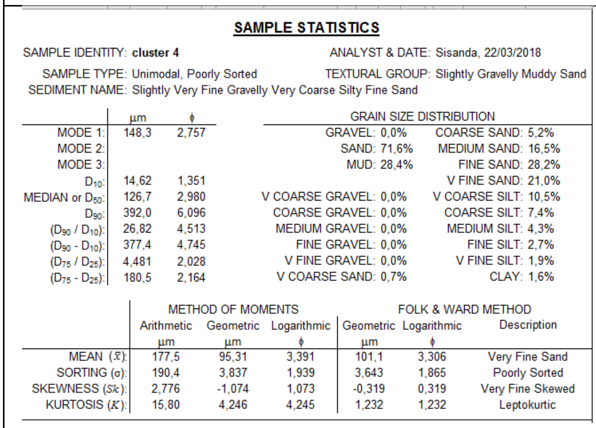
	µm	ϕ
MODE 1:	170,2	2,558
MODE 2:	21,43	5,548
MODE 3:		
D_{10}:	11,25	1,537
MEDIAN or D_{50}:	138,1	2,856
D_{90}:	344,5	6,474
(D_{90} / D_{10}):	30,62	4,211
$(D_{90} - D_{10})$:	333,2	4,936
(D_{75} / D_{25}):	3,656	1,879
$(D_{75} - D_{25})$:	166,2	1,870

GRAIN SIZE DISTRIBUTION

GRAVEL:	0,0%	COARSE SAND:	2,9%
SAND:	75,0%	MEDIUM SAND:	18,0%
MUD:	25,0%	FINE SAND:	33,5%
		V FINE SAND:	20,4%
V COARSE GRAVEL:	0,0%	V COARSE SILT:	6,6%
COARSE GRAVEL:	0,0%	COARSE SILT:	5,9%
MEDIUM GRAVEL:	0,0%	MEDIUM SILT:	4,6%
FINE GRAVEL:	0,0%	FINE SILT:	3,3%
V FINE GRAVEL:	0,0%	V FINE SILT:	2,4%
V COARSE SAND:	0,2%	CLAY:	2,1%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic	Geometric	Logarithmic	Geometric	Logarithmic	Description
	µm	µm	ϕ	µm	ϕ	
MEAN ($\bar{x}$):	166,1	93,49	3,419	97,81	3,354	Very Fine Sand
SORTING (σ):	146,7	3,970	1,989	3,734	1,901	Poorly Sorted
SKEWNESS (Sk):	2,057	-1,363	1,363	-0,459	0,459	Very Fine Skewed
KURTOSIS (K):	12,48	4,564	4,564	1,454	1,454	Leptokurtic





SAMPLE STATISTICS

SAMPLE IDENTITY: **cluster 4** ANALYST & DATE: Sisanda, 22/03/2018

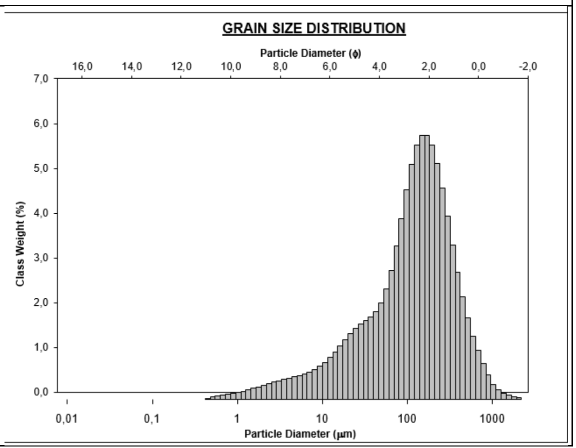
SAMPLE TYPE: Unimodal, Poorly Sorted TEXTURAL GROUP: Slightly Gravelly Muddy Sand
SEDIMENT NAME: Slightly Very Fine Gravelly Very Coarse Silty Fine Sand

	µm	ϕ
MODE 1:	148,3	2,757
MODE 2:		
MODE 3:		
D_{10}:	14,62	1,351
MEDIAN or D_{50}:	126,7	2,980
D_{90}:	392,0	6,096
(D_{90} / D_{10}):	26,82	4,513
$(D_{90} - D_{10})$:	377,4	4,745
(D_{75} / D_{25}):	4,481	2,028
$(D_{75} - D_{25})$:	180,5	2,164

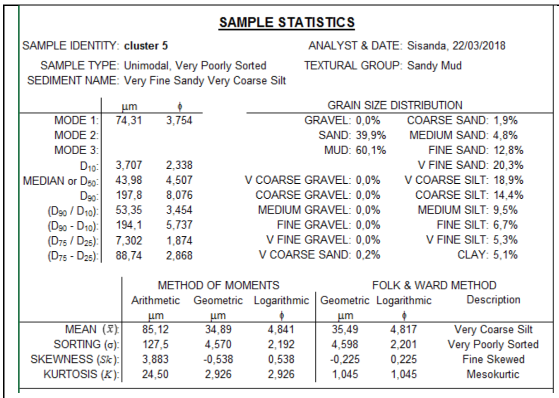
GRAIN SIZE DISTRIBUTION

GRAVEL:	0,0%	COARSE SAND:	5,2%
SAND:	71,6%	MEDIUM SAND:	16,5%
MUD:	28,4%	FINE SAND:	28,2%
		V FINE SAND:	21,0%
V COARSE GRAVEL:	0,0%	V COARSE SILT:	10,5%
COARSE GRAVEL:	0,0%	COARSE SILT:	7,4%
MEDIUM GRAVEL:	0,0%	MEDIUM SILT:	4,3%
FINE GRAVEL:	0,0%	FINE SILT:	2,7%
V FINE GRAVEL:	0,0%	V FINE SILT:	1,9%
V COARSE SAND:	0,7%	CLAY:	1,6%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic	Geometric	Logarithmic	Geometric	Logarithmic	Description
	µm	µm	ϕ	µm	ϕ	
MEAN ($\bar{x}$):	177,5	95,31	3,391	101,1	3,306	Very Fine Sand
SORTING (σ):	190,4	3,837	1,939	3,643	1,865	Poorly Sorted
SKEWNESS (Sk):	2,776	-1,074	1,073	-0,319	0,319	Very Fine Skewed
KURTOSIS (K):	15,80	4,246	4,245	1,232	1,232	Leptokurtic



Cluster 5 -8



SAMPLE STATISTICS

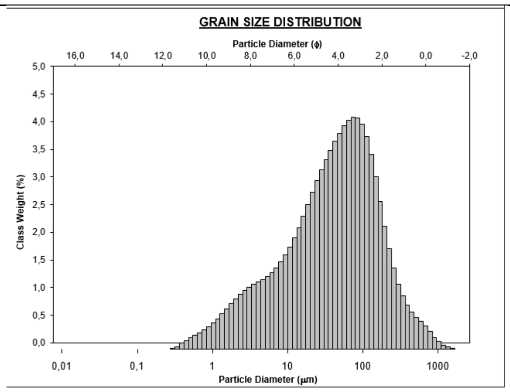
SAMPLE IDENTITY: **cluster 5**
ANALYST & DATE: Sisanda, 22/03/2018
SAMPLE TYPE: Unimodal, Very Poorly Sorted
TEXTURAL GROUP: Sandy Mud
SEDIMENT NAME: Very Fine Sandy Very Coarse Silt

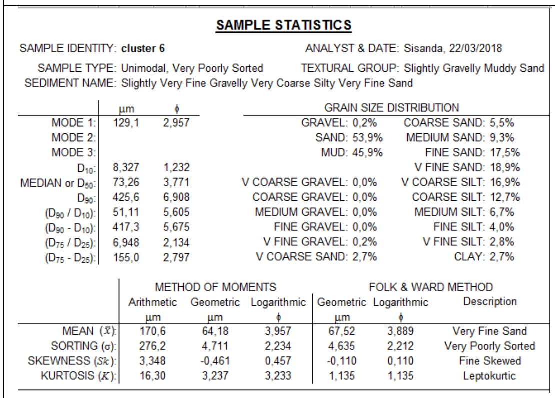
	µm	ϕ
MODE 1:	74,31	3,754
MODE 2:		
MODE 3:		
D_{10}:	3,707	2,338
MEDIAN or D_{50}:	43,98	4,507
D_{90}:	197,8	8,076
(D_{90} / D_{10}):	53,35	3,454
(D_{90} - D_{10}):	194,1	5,737
(D_{75} / D_{25}):	7,302	1,874
(D_{75} - D_{25}):	88,74	2,868

GRAIN SIZE DISTRIBUTION

GRAVEL:	0,0%	COARSE SAND:	1,9%
SAND:	39,9%	MEDIUM SAND:	4,8%
MUD:	60,1%	FINE SAND:	12,8%
		V FINE SAND:	20,3%
V COARSE GRAVEL:	0,0%	V COARSE SILT:	18,9%
COARSE GRAVEL:	0,0%	COARSE SILT:	14,4%
MEDIUM GRAVEL:	0,0%	MEDIUM SILT:	9,5%
FINE GRAVEL:	0,0%	FINE SILT:	6,7%
V FINE GRAVEL:	0,0%	V FINE SILT:	5,3%
V COARSE SAND:	0,2%	CLAY:	5,1%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic µm	Geometric µm	Logarithmic ϕ	Geometric µm	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	85,12	34,89	4,841	35,49	4,817	Very Coarse Silt
SORTING (σ):	127,5	4,570	2,192	4,598	2,201	Very Poorly Sorted
SKEWNESS (Sk):	3,883	-0,538	0,538	-0,225	0,225	Fine Skewed
KURTOSIS (K):	24,50	2,926	2,926	1,045	1,045	Mesokurtic





SAMPLE STATISTICS

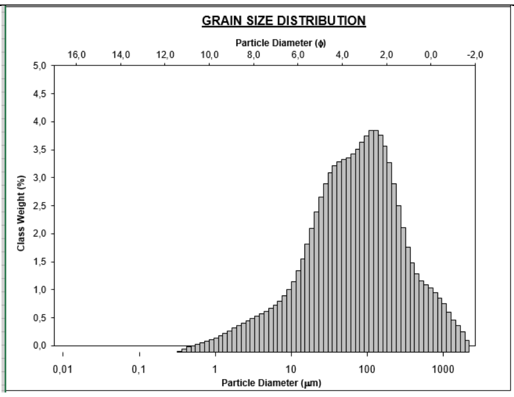
SAMPLE IDENTITY: **cluster 6**
ANALYST & DATE: Sisanda, 22/03/2018
SAMPLE TYPE: Unimodal, Very Poorly Sorted
TEXTURAL GROUP: Slightly Gravelly Muddy Sand
SEDIMENT NAME: Slightly Very Fine Gravelly Very Coarse Silty Very Fine Sand

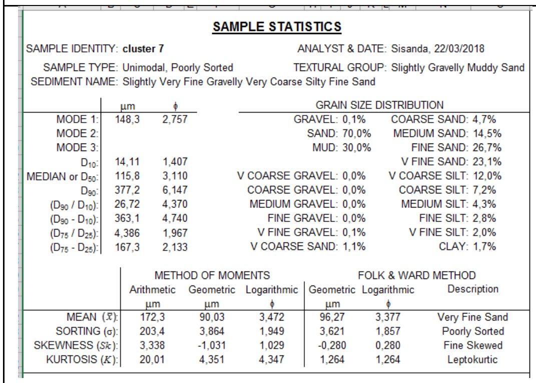
	µm	ϕ
MODE 1:	129,1	2,957
MODE 2:		
MODE 3:		
D_{10}:	8,327	1,232
MEDIAN or D_{50}:	73,26	3,771
D_{90}:	425,6	6,908
(D_{90} / D_{10}):	51,11	5,605
(D_{90} - D_{10}):	417,3	5,675
(D_{75} / D_{25}):	6,948	2,134
(D_{75} - D_{25}):	155,0	2,797

GRAIN SIZE DISTRIBUTION

GRAVEL:	0,2%	COARSE SAND:	5,5%
SAND:	53,9%	MEDIUM SAND:	9,3%
MUD:	45,9%	FINE SAND:	17,5%
		V FINE SAND:	18,9%
V COARSE GRAVEL:	0,0%	V COARSE SILT:	16,9%
COARSE GRAVEL:	0,0%	COARSE SILT:	12,7%
MEDIUM GRAVEL:	0,0%	MEDIUM SILT:	6,7%
FINE GRAVEL:	0,0%	FINE SILT:	4,0%
V FINE GRAVEL:	0,2%	V FINE SILT:	2,8%
V COARSE SAND:	2,7%	CLAY:	2,7%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic µm	Geometric µm	Logarithmic ϕ	Geometric µm	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	170,6	64,18	3,957	67,52	3,889	Very Fine Sand
SORTING (σ):	276,2	4,711	2,234	4,635	2,212	Very Poorly Sorted
SKEWNESS (Sk):	3,348	-0,461	0,457	-0,110	0,110	Fine Skewed
KURTOSIS (K):	16,30	3,237	3,233	1,135	1,135	Leptokurtic





SAMPLE STATISTICS

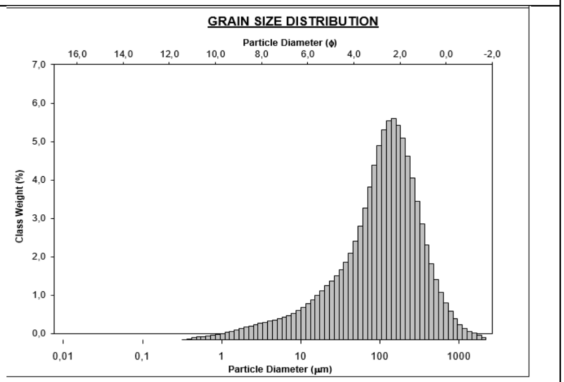
SAMPLE IDENTITY: **cluster 7**
ANALYST & DATE: Sisanda, 22/03/2018
SAMPLE TYPE: Unimodal, Poorly Sorted
TEXTURAL GROUP: Slightly Gravelly Muddy Sand
SEDIMENT NAME: Slightly Very Fine Gravelly Very Coarse Silty Fine Sand

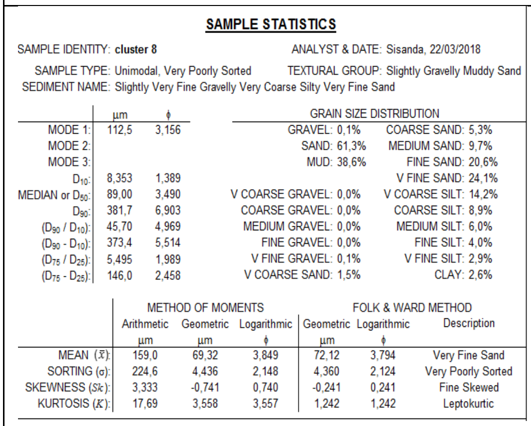
	µm	ϕ
MODE 1:	148,3	2,757
MODE 2:		
MODE 3:		
D_{10}:	14,11	1,407
MEDIAN or D_{50}:	115,8	3,110
D_{90}:	377,2	6,147
(D_{90} / D_{10}):	26,72	4,370
(D_{90} - D_{10}):	363,1	4,740
(D_{75} / D_{25}):	4,386	1,967
(D_{75} - D_{25}):	167,3	2,133

GRAIN SIZE DISTRIBUTION

GRAVEL:	0,1%	COARSE SAND:	4,7%
SAND:	70,0%	MEDIUM SAND:	14,5%
MUD:	30,0%	FINE SAND:	26,7%
		V FINE SAND:	23,1%
V COARSE GRAVEL:	0,0%	V COARSE SILT:	12,0%
COARSE GRAVEL:	0,0%	COARSE SILT:	7,2%
MEDIUM GRAVEL:	0,0%	MEDIUM SILT:	4,3%
FINE GRAVEL:	0,0%	FINE SILT:	2,8%
V FINE GRAVEL:	0,1%	V FINE SILT:	2,0%
V COARSE SAND:	1,1%	CLAY:	1,7%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic µm	Geometric µm	Logarithmic ϕ	Geometric µm	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	172,3	90,03	3,472	96,27	3,377	Very Fine Sand
SORTING (σ):	203,4	3,864	1,949	3,621	1,857	Poorly Sorted
SKEWNESS (Sk):	3,338	-1,031	1,029	-0,280	0,280	Fine Skewed
KURTOSIS (K):	20,01	4,351	4,347	1,264	1,264	Leptokurtic





SAMPLE STATISTICS

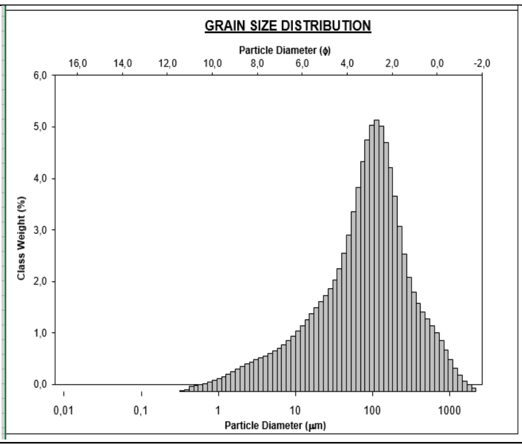
SAMPLE IDENTITY: **cluster 8**
ANALYST & DATE: Sisanda, 22/03/2018
SAMPLE TYPE: Unimodal, Very Poorly Sorted
TEXTURAL GROUP: Slightly Gravelly Muddy Sand
SEDIMENT NAME: Slightly Very Fine Gravelly Very Coarse Silty Very Fine Sand

	µm	ϕ
MODE 1:	112,5	3,156
MODE 2:		
MODE 3:		
D_{10}:	8,353	1,389
MEDIAN or D_{50}:	89,00	3,490
D_{90}:	381,7	6,903
(D_{90} / D_{10}):	45,70	4,969
(D_{90} - D_{10}):	373,4	5,514
(D_{75} / D_{25}):	5,495	1,989
(D_{75} - D_{25}):	146,0	2,458

GRAIN SIZE DISTRIBUTION

GRAVEL:	0,1%	COARSE SAND:	5,3%
SAND:	61,3%	MEDIUM SAND:	9,7%
MUD:	38,6%	FINE SAND:	20,6%
		V FINE SAND:	24,1%
V COARSE GRAVEL:	0,0%	V COARSE SILT:	14,2%
COARSE GRAVEL:	0,0%	COARSE SILT:	8,9%
MEDIUM GRAVEL:	0,0%	MEDIUM SILT:	6,0%
FINE GRAVEL:	0,0%	FINE SILT:	4,0%
V FINE GRAVEL:	0,1%	V FINE SILT:	2,9%
V COARSE SAND:	1,5%	CLAY:	2,6%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic µm	Geometric µm	Logarithmic ϕ	Geometric µm	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	159,0	69,32	3,849	72,12	3,794	Very Fine Sand
SORTING (σ):	224,6	4,436	2,148	4,360	2,124	Very Poorly Sorted
SKEWNESS (Sk):	3,333	-0,741	0,740	-0,241	0,241	Fine Skewed
KURTOSIS (K):	17,69	3,558	3,557	1,242	1,242	Leptokurtic



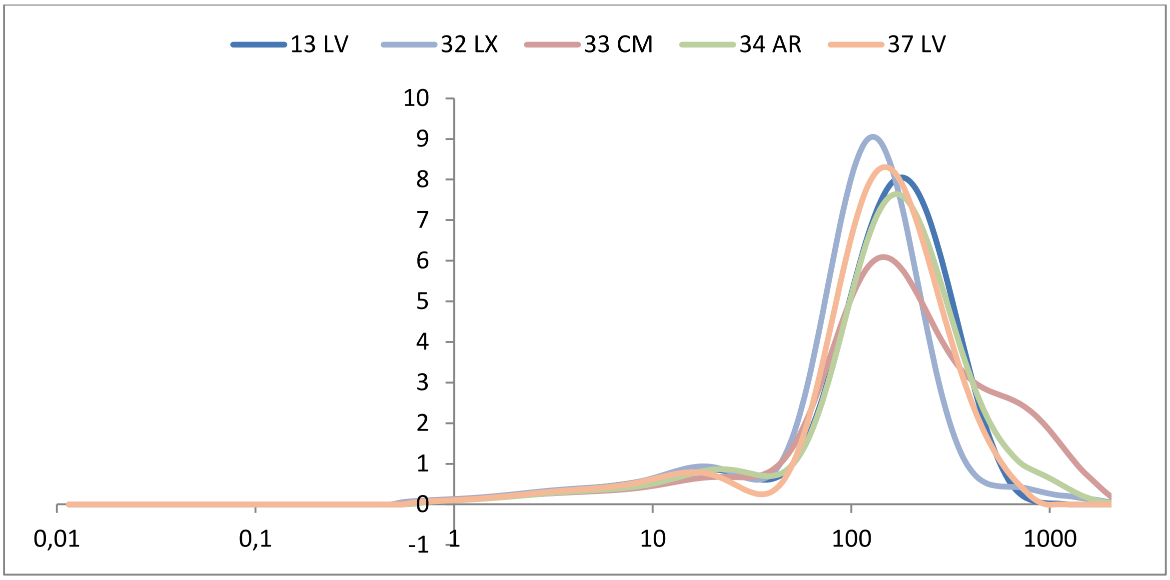


Figure A3.2: The above figure shows the first cluster (cluster 1). Five samples fall on this cluster two of them being the Luvisols

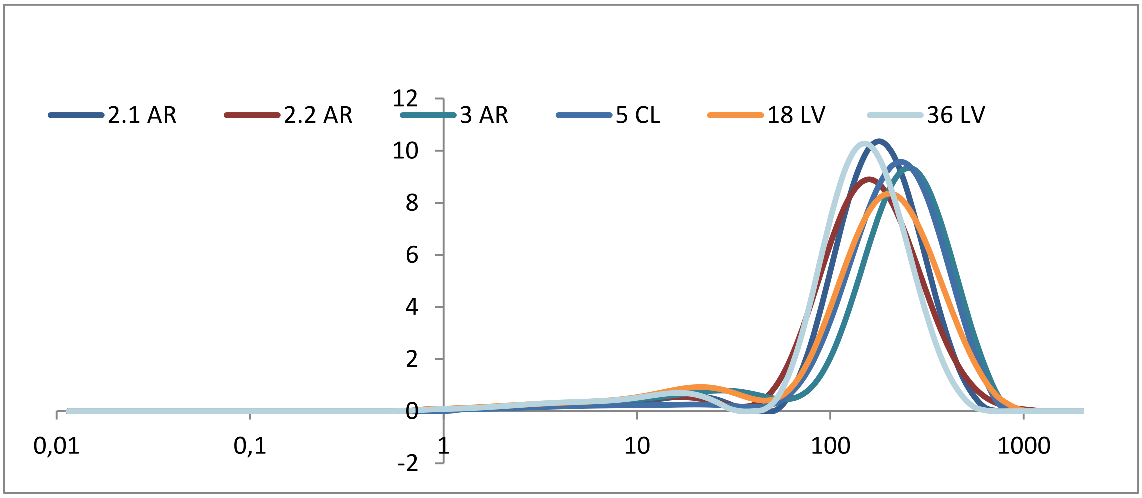


Figure A3.3: The second Cluster (cluster 2) has six samples, three of the samples being the Arenosols and two samples being the Luvisols

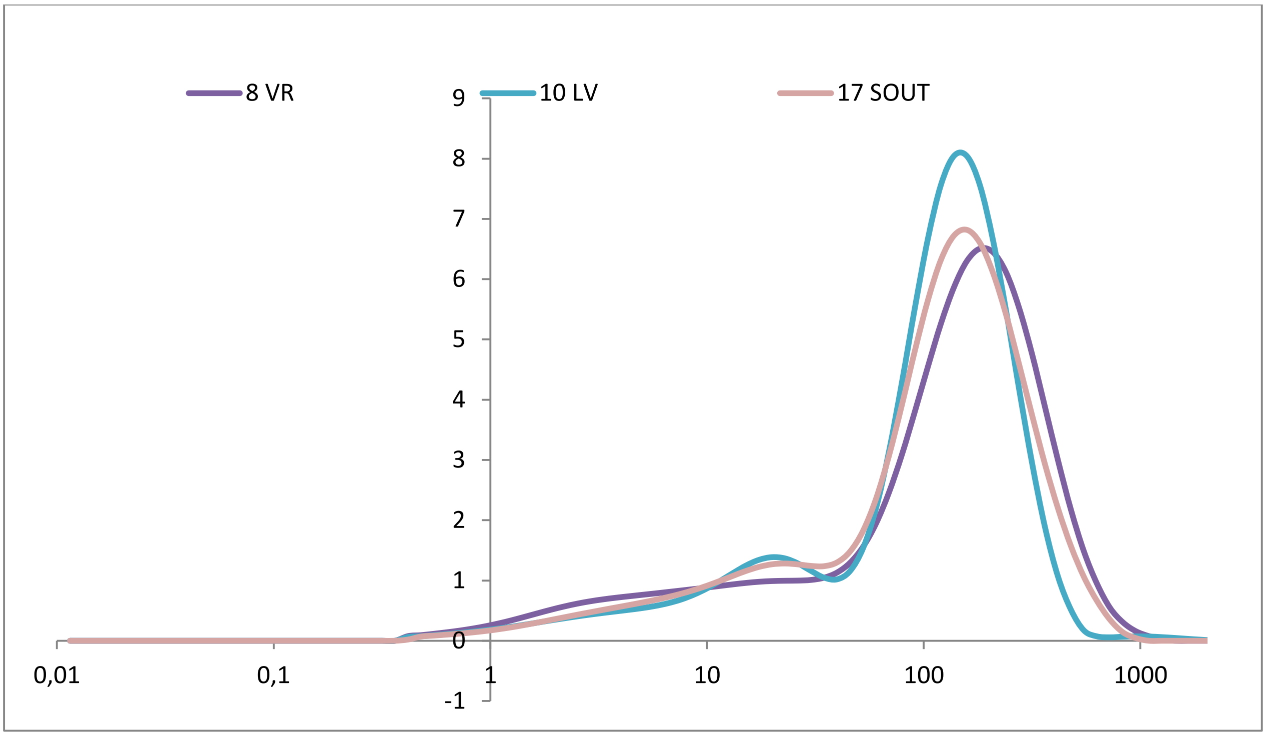


Figure A3.4: Three samples were found in cluster 3

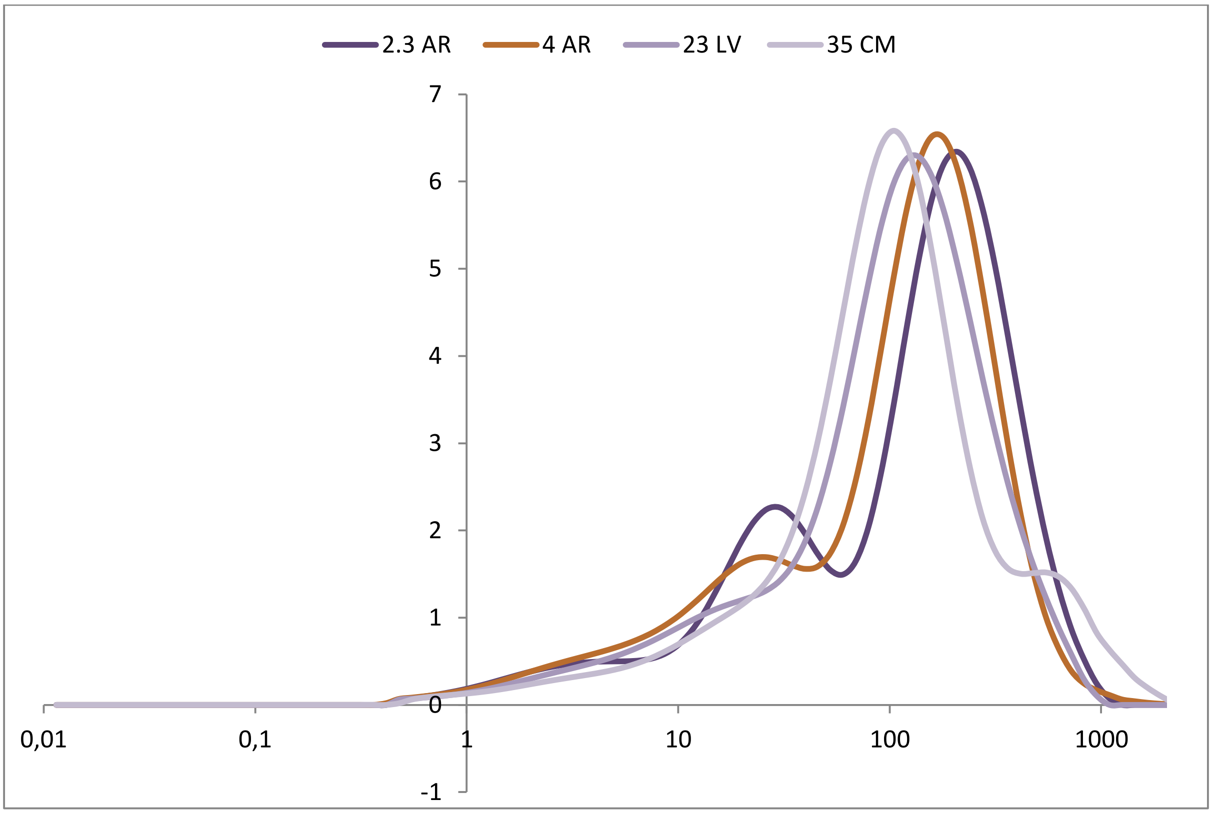


Figure A3.5: Cluster 4 is dominated by the Arenosols in the four samples that it had

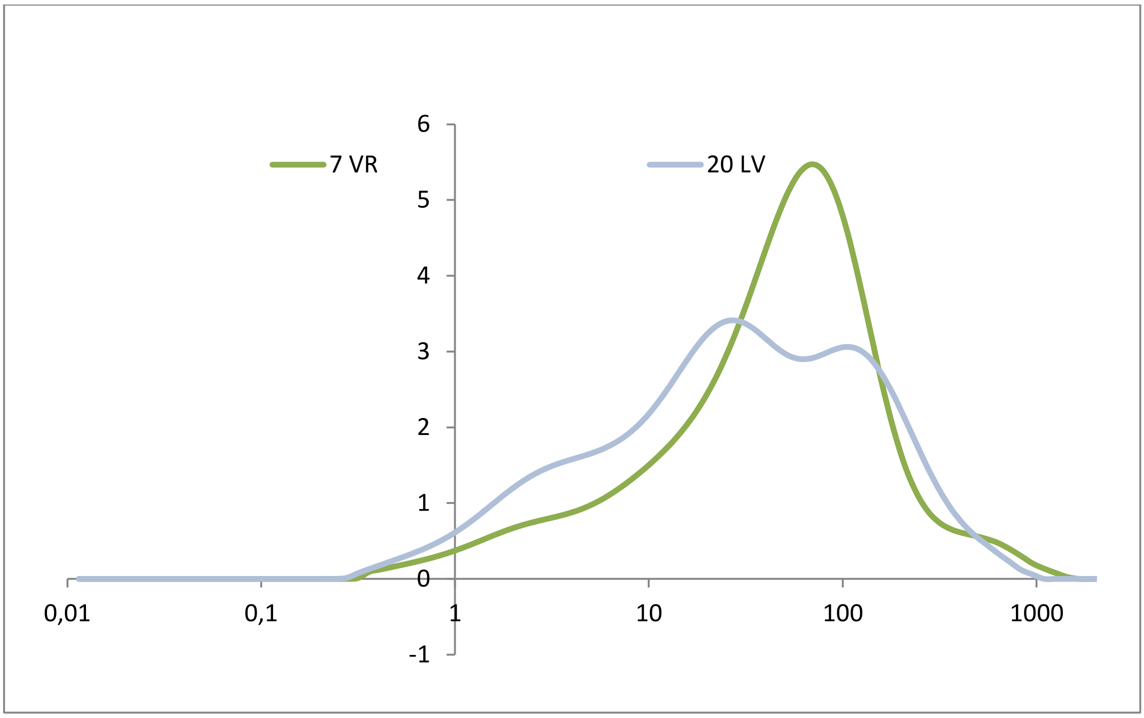
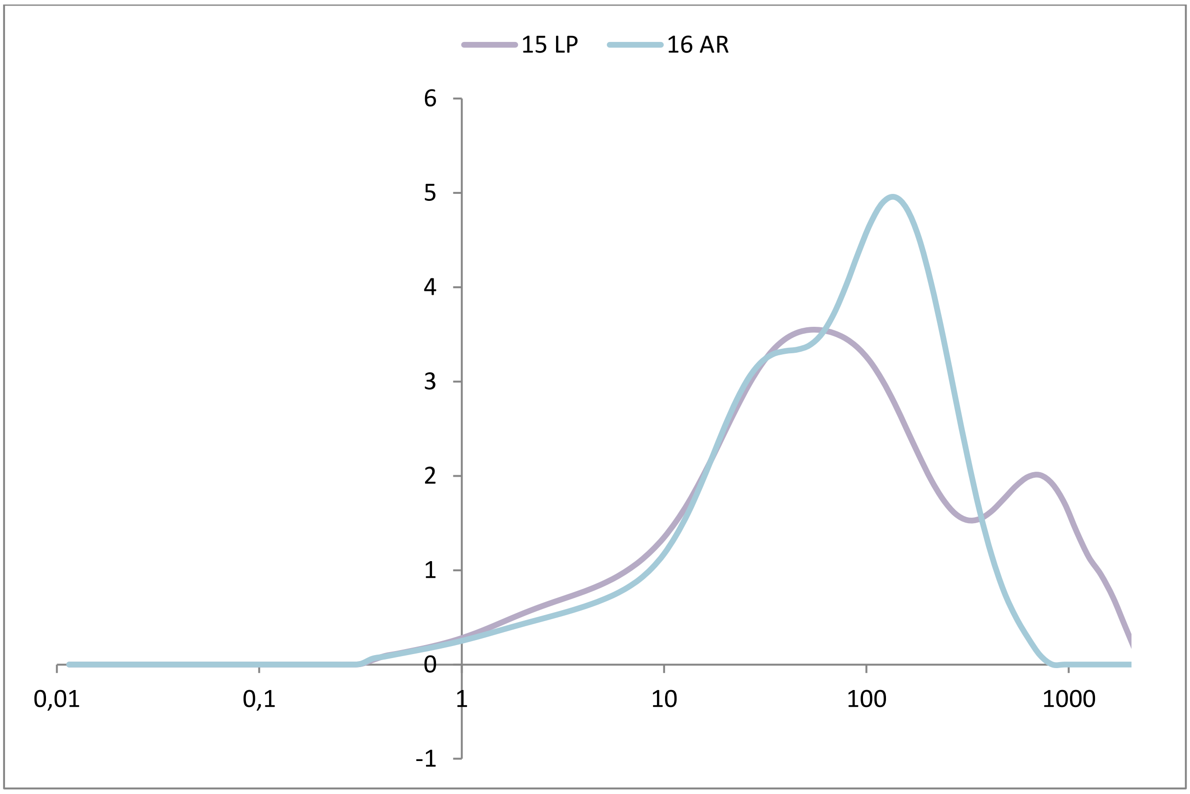


Figure A3.6: Two samples were found in Cluster 5.



FigureA3.7: Arenosols and Leptosols are found in cluster 6. Leptosols are not likely to be emissive soils. This is because they are generally extremely gravelly and stone.

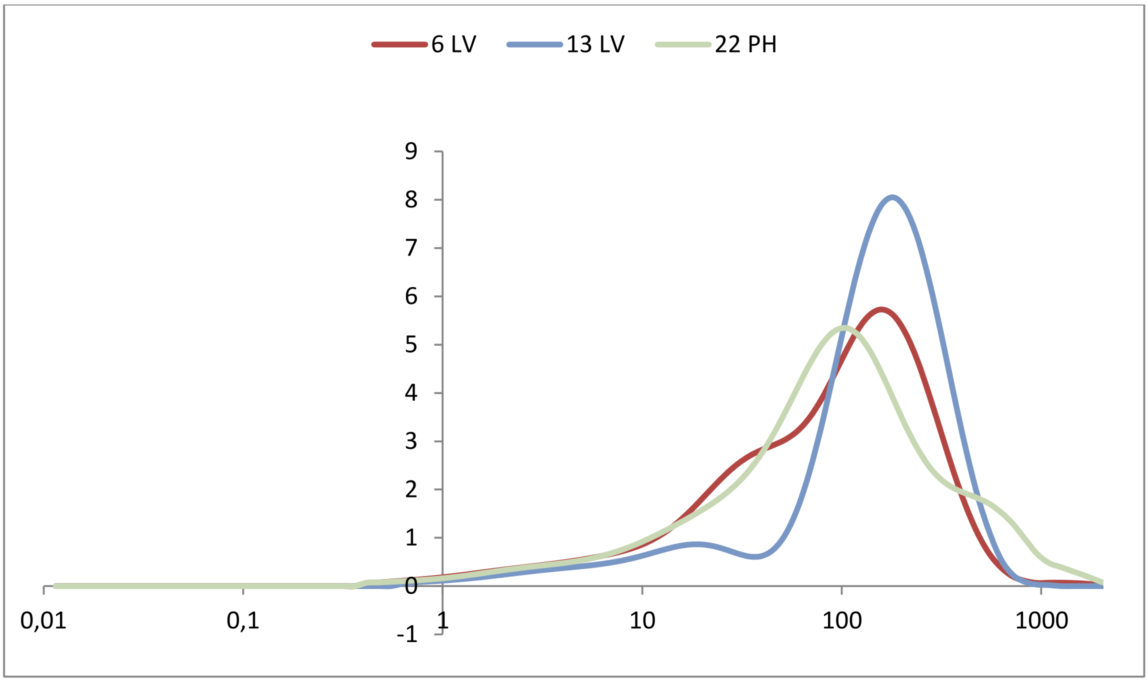


Figure A3.8: Three samples are found in cluster 7.The Luvisols are the dominant soils

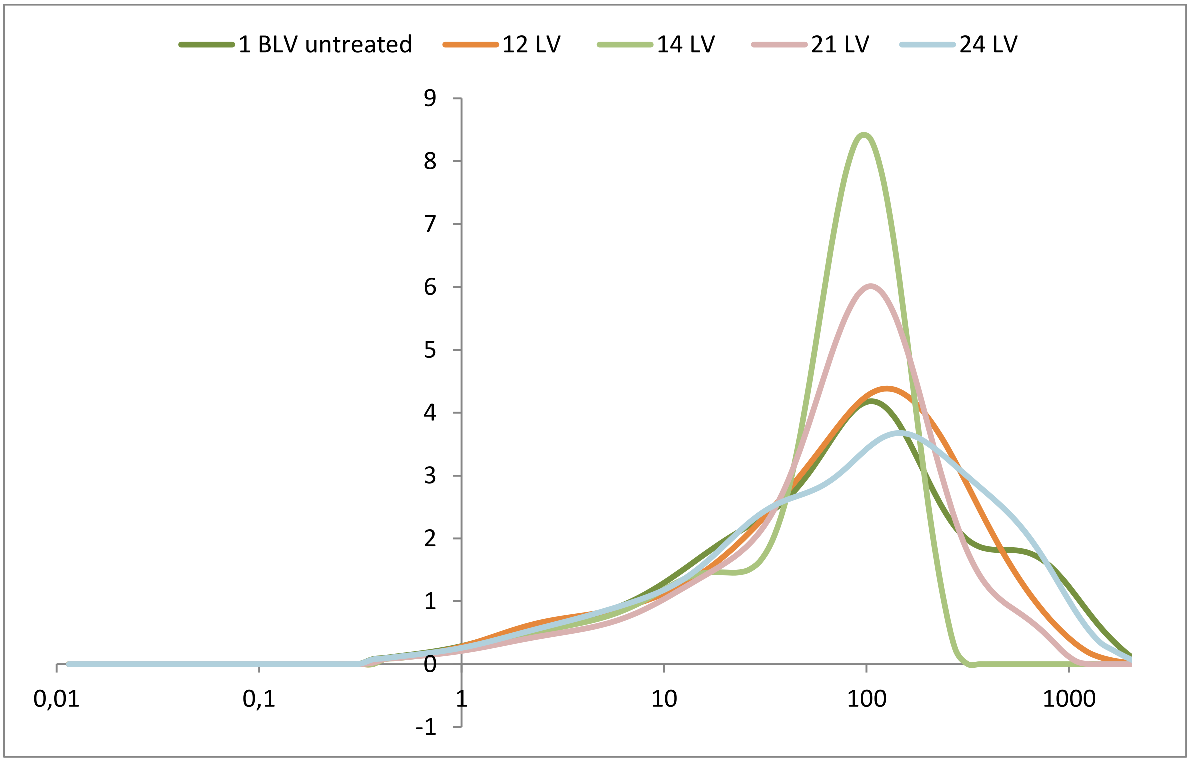


Figure A3.9: Cluster 8 has five samples with all of them being the Luvisols. From the previous chapter these soils are known to be highly emissive because of the land uses practiced in these soils.

Table A3.4 Soil Texture Obtained from Custer Analyses

	< 2	2to10	10to63	63to100	100to1000	>1000	Clay	Silt	Sand
Cluster 1	1	4	11	13	68	2	6	11	83
Cluster 2	1	4	6	8	81	0	4	6	89
Cluster 3	2	8	16	11	62	0	10	16	73
Cluster 4	2	6	22	12	57	1	8	22	69
Cluster 5	6	16	41	12	24	0	22	41	37
Cluster 6	3	10	36	11	38	2	13	36	51
Cluster 7	2	7	24	14	53	1	9	24	68
Cluster 8	3	9	29	14	43	1	13	29	58

Table A3.5 Soil samples sand/silt ratios

Sample	% SAND:	% MUD:	Ratio
01 LV	0,591	0,408	1
02.1 AR	0,924	0,076	12
02.2 AR	0,894	0,106	8
02.3 AR	0,707	0,293	2
03 AR	0,877	0,123	7
04 Clpt	0,709	0,291	2
05 AR	0,945	0,055	17
06 LV	0,65	0,349	2
07 VR	0,447	0,553	1
08 VR	0,747	0,253	3
10 LV	0,759	0,241	3
12 LV	0,608	0,392	2
13 LV	0,84	0,16	5
14 VR	0,624	0,376	2
15 LP	0,523	0,474	1
16 AR	0,556	0,444	1
17 CL	0,745	0,255	3
18 LX	0,862	0,138	6
20 LV/VR	0,352	0,648	1
21 LV/VR	0,634	0,366	2
22 PH	0,658	0,341	2

23 LV	0,727	0,273	3
24 LV	0,609	0,39	2
31 LX	0,65	0,349	2
32 LXfr	0,817	0,182	4
33 AR	0,85	0,148	6
34 AR	0,851	0,149	6
35 CM	0,719	0,28	3
36 LV	0,899	0,101	9
37 LV	0,861	0,139	6