Characterising the impact of rainfall on dustfall rates

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Abstract
Soil moisture increased the cohesion potential between particles, reducing the ability of the particle to be entrained. Dust suppression techniques are designed to increase soil moisture and therefore soil cohesion through the application of water or water-based chemicals to surfaces that have known potential for dust entrainment. Rainfall has the ability to act as a natural dust suppression mechanism; however, there is a paucity of literature on the actual effectiveness of rainfall in this regard. The ASTM D1739 methods for dustfall monitoring, commonly used in South Africa, and the National Dust Control Regulations (2013), both state that rainfall should be recorded when conducting dustfall monitoring. The rationale is that rainfall or the absence thereof, results in lower or higher dustfall rates, respectively. A suitable study site was identified in Mpumalanga, South Africa. This site had eight non-directional dustfall samplers in the near vicinity of an air quality monitoring station. Dustfall results from the eight samplers were analysed based on four scenarios, two that considers the presence of rainfall and two that consider the absence of rainfall. This analysis was further combined with wind speed data. This study, over a 24-month period indicates that there is no substantial evidence that above average rainfall will result in below average dustfall. This occurred for one month out of 24 months. Conversely, there is no consensus that the absence of rainfall will result in higher dustfall rates, which occurred cumulatively 30% of the time. Additional environmental and / or operational information may have a greater influence on dustfall compared to rainfall. Careful consideration should be taken to prevent misrepresentation of causational effects of rainfall on dustfall results. Management of dust should be undertaken through dust mitigation measures irrespective of the natural rainfall regime.

Keywords
Dustfall, air quality, ASTM D1739, Rainfall, dust suppression, South Africa

Introduction
Soil moisture increases the cohesion between soil particles increasing the resistance of soil particles to wind-blown entrainment and erosion (Wiggs, Baird and Atherton 2004). Wind tunnel studies of moisture content and wind speeds have allowed for the development of critical moisture thresholds (Han et al. 2009; McKenna-Neuman and Nickling 1989). The critical threshold is the moisture content value whereby the potential for entrainment and sediment transport is suppressed (Wiggs, Baird and Atherton 2004) albeit with a wide variation of results (Namikas and Sherman 1995).

Fugitive dust suppression techniques aim reducing the materials erodibility by increasing soil moisture content and / or soil cohesion through the application of water and water-based chemicals to sources of dust (Thompson and Visser 2002; Tsai, Lee and Lin 2003). Rainfall has the ability to act as a natural dust suppressant through the same mechanism and anthropogenic dust control measures. However, there is a paucity of data on the effectiveness of rainfall as a natural dust suppressant mechanism.

South Africa promulgated the National Dust Control Regulations (NDCR) in 2013 (South Africa 2013), which specifies the acceptable dustfall rates within Residential and Non-Residential areas. Furthermore, the NDCR states the monitoring methodology and the reporting requirements. Of interest in this study, is the requirement for rainfall to be included in dustfall reports (ASTM 1970; South Africa 2013). The implication of requiring knowledge on rainfall during a dustfall monitoring survey suggests that rainfall has the ability to impact dustfall rates. The hypothesis is that rainfall should reduce dustfall rates through increased soil moisture, which increases soil cohesion thus reduces the potential for wind-blown entrainment (Wiggs and Holmes 2011).

This study aims to test this hypothesis and subsequently to improve our understanding of the importance of including and discussing rainfall in relation to dustfall results.

Study Site
The actual study site is undisclosed for confidentiality reasons. The study site is located within the Mpumalanga Province, South Africa. The broader area surrounding the study site (approximately 15 km radius) includes formal and informal settlements, mining, agriculture and power generation.

A dustfall network comprised of eight non-directional dustfall samplers without windshields was strategically located based on the objectives of the air quality monitoring plan. This resulted in the closest dustfall sampler being located approximately 1 km from an ambient air quality monitoring station (AQMS), while the furthest sampler was located approximately 10 km from the AQMS.

The samplers, in relation to each other, are on average 8 km apart, with the furthest distance 17 km. The primary and secondary sources of dustfall for each site is provided (Table 1). Primary sources of dustfall are agriculture and mining while two sites could be considered as baseline monitoring due to their location within either residential or smallholding areas. Secondary sources of dustfall include large-scale industrial development, mining and agricultural activities.

***Table 1**: Primary and secondary sources of dustfall for each site.*

Site	Primary source	Secondary source
Site 01	Agriculture	Large-scale construction (~10 km2)
Site 02	Agriculture	Large-scale construction (~10 km2)
Site 03	Mine haulage road	Large-scale construction (~10 km2)
Site 04	None; residential	None
Site 05	Agriculture and waste rock stockpile	None
Site 06	None; smallholding	Coal mining
Site 07	Agriculture	None
Site 08	Sand mining	Agriculture

The AQMS monitors various meteorological and pollutant parameters. The parameters pertinent to this study include rainfall, wind speed and wind direction, which were monitored using a MetOne 300 series (rainfall) and MetOne 034B (winds).

Dustfall monitoring networks are typically developed to monitor the potential for wind-blown dust from specific sources, such as tailings dams, stockpiles and roads. As such, it is useful to analyse data from the network as a whole unit, instead of analysing each individual samplers. This process allows for improved understanding of regional impacts on the individual dustfall units. However, this study site provides challenges in conducting this type of analysis due to the multiple sources of dustfall.

Methods

Dustfall and Meteorological Monitoring

Dustfall monitoring commenced in November 2011 at all eight sites and continued until April 2015. The same type of sampler and collector (buckets) were used throughout the study. All collectors were positioned at above 2 m from ground-level. The sample preparation and analysis were conducted in accordance with the ASTM D1739 requirements (ASTM 1970).

Meteorological monitoring commenced in December 2012 and continued until April 2015. The rain gauge was attached to the top of the AQMS, approximately 2 m above ground, while the wind sensor was located on a mast, approximately 5 m above ground.

Data from the dustfall monitoring was collected on monthly basis, while the rainfall and wind data was collected at 5-minute averages.

Rainfall and meteorological data was analysed for the period January 2013 to December 2014, where both datasets were concurrently operational. In addition, the time-period would allow for two full years to be analysed.

Dustfall

The monthly dustfall rates from each site, over the two-year period, were averaged to determine baseline dustfall data per month. Each month's dustfall data was compared to the monthly average to determine whether the observed dustfall rates were above or below the baseline average.

Rainfall

Rainfall data from four meteorological stations managed by the Department of Water and Sanitation (DWS) was collected to determine baseline rainfall for the dustfall network (Department of Water and Sanitation 2008). The four stations are located between 20 and 50 km from the dustfall network and had rainfall data extending back to 1962 (one station).

Observed rainfall data was for the dustfall network was collected from the AQMS. The observed rainfall for each month (January 2013 to December 2014) was compared to the baseline data to determine if the observed rainfall was above or below the baseline average.

Data analysis

Dustfall and rainfall for each month was compared to the baseline dustfall and rainfall. Based on this process, four scenarios were identified:

1. Rainfall reduces dustfall rates when monthly dustfall rates are below average and rainfall is above average;
2. Rainfall does not reduce dustfall rates when monthly dustfall rates are above average and monthly rainfall is above average;
3. The absence of rainfall may increase dustfall rates when the monthly dustfall rates are above average and monthly rainfall is below average; and
4. The absence of rain does not increase dustfall when monthly dustfall rates are below average and rainfall is below average.

This process was conducted under two conditions, 1) conservative and 2) stringent:

1. The conservative approach considered all valid data points for each site for each month. Each individual dustfall point was compared to the monthly rainfall and classified into one of the four scenarios. This enabled all data points (186 valid points) to be used in the analysis.
2. The stringent approach was applied where all eight sites exhibited the same trend (e.g., all eight sites had recorded

above-average dustfall rates). The premise for this approach is that the dustfall network should be considered as whole unit and that all sites should exhibit the same trend, which could indicate regional conditions. As such, only 80 valid points were used in this analysis.

Additional data was analysed in attempt to further understand the findings within each of the scenarios, including;
a) The total rainfall [mm]; and
b) The average monthly wind speed [m/s].

Results

Rainfall

The study site is located in a summer rainfall region of South Africa. The average seasonal rainfall (DWS Rainfall) and the observed seasonal rainfall follows the expected rainfall trends for a summer rainfall area (Table 2).

***Table 2**: Average Seasonal Rainfall [mm] from the DWS Stations (Department of Water and Sanitation 2008) and the observed rainfall from site.*

Season	Months (abbr.)	Rainfall [mm]	
		Baseline	Observed
Summer	DJF	119	110
Autumn	MAM	50	62
Winter	JJA	10	1
Spring	SON	79	82

Further correlation was between observed rainfall per month as a function of the baseline data and average observed monthly rainfall as a function of the baseline data was conducted. The findings indicate a R2 of 0.65 and 071 respectively. The correlation between monthly-observed rainfall as a function of the baseline rainfall was further analysed in terms of seasonal trends. All winter months experienced below average rainfall whilst all other seasons contained a variation of above average and below average rainfall (Figure 1).

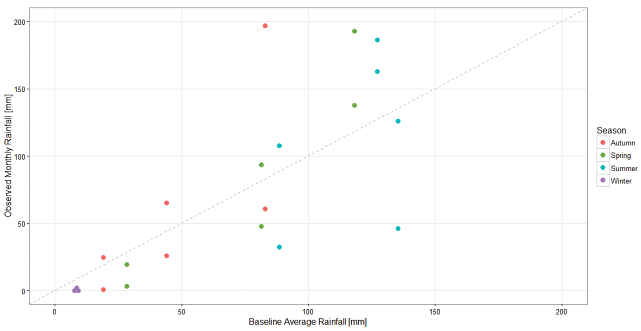

***Figure 1:** Comparison of observed monthly rainfall (y-axis) with long-term monthly-averaged rainfall (x-axis) from the Department of Water and Sanitation (2008) with the colours representing the seasons.*

The correlation between the two datasets suggests that the rainfall experienced at site were representative of typical rainfall conditions in the area. Above average rainfall on a monthly basis occurred nine out of 24 months (Table 3).

Wind speeds

Average monthly wind speeds over the two-year period ranged between 1.6 and 3.2 m/s. Average seasonal winds range from Autumn (1.8 m/s) to Spring (2.9 m/s). The higher winds during Spring are consistent with typical conditions on the Highveld.

***Table 3**: Above (blue) and below (red) average rainfall occurrences*

January 2013	February 2013	March 2013	April 2013
May 2013	June 2013	July 2013	August 2013
September 2013	October 2013	November 2013	December 2013
January 2014	February 2014	March 2014	April 2014
May 2014	June 2014	July 2014	August 2014
September 2014	October 2014	November 2014	December 2014

Dustfall

The total number of valid dustfall rates was 186 out of a maximum of 192. The 186-dustfall rates were analysed. The observed monthly rainfall at site for all months was plotted as a function of observed monthly dustfall rates (Figure 2). The graph indicates a wide range of rainfall and dustfall rates above and below the average rainfall and dustfall rates (blue).

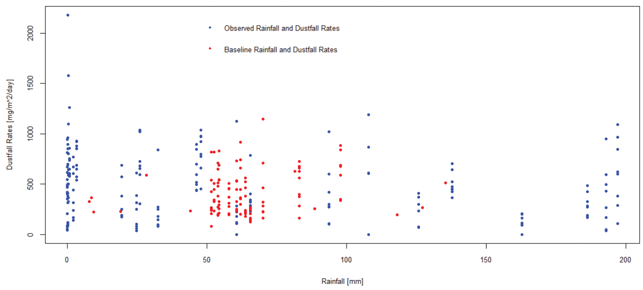

***Figure 2:** Dustfall rates as a function of rainfall for observed monthly data (red) and averaged data dustfall and rainfall (blue).*

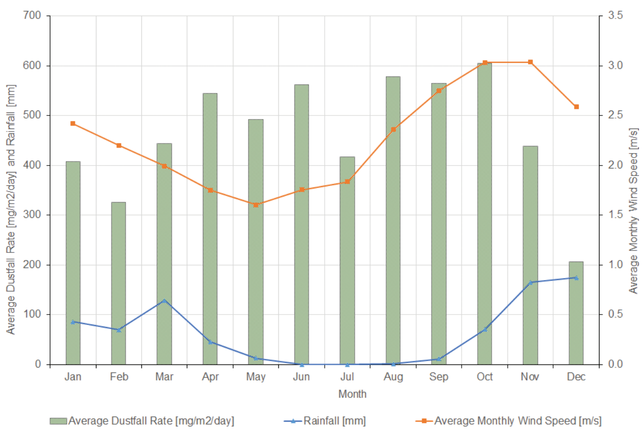

***Figure 3:** Monthly averaged dustfall rates (green bars), total monthly rainfall (blue line) and averaged wind speeds (red line).*

The averaged dustfall rates, monthly wind speeds and observed rainfall was plotted (Figure 3). This graph clearly illustrates the expected meteorological trends characteristic of the Highveld. Wind speeds increased from the end of August, peaking in

October / November. Rainfall increases from Spring through to Summer and declines sharply during Autumn, with little to no rainfall occurring during the Winter periods. The average monthly dustfall indicates two peaks, April to June and August to October. Whilst the average rainfall for these two peaks is similar (20 versus 28 mm, respectively), these two peaks have contrasting average wind speeds (1.7 versus 2.7 m/s, respectively).

A comparison of each scenario was performed considering the conservative approach (Table 4), where all data was considered, and the stringent approach (Table 5), where only those periods where the entire network responded in the same way. The average wind speed, total rainfall and the frequency of occurrence to each scenario (valid counts) was analysed. The two approaches indicate similar trends in valid counts; however, there is a marked contrast in the average rainfall and wind speeds for each approach.

The original hypothesis, that increased rainfall should reduce dustfall, occurs the least amount of times in both approaches.

Table 4*: Statistics for each of the four scenarios under conservative approach.*

Scenario	Valid counts [%]	Average Rainfall [mm]	Average Monthly Wind speed [m/s]
1	15	142	2.4
2	17	143	2.5
3	35	20	2.1
4	33	28	2.2

Table 5*: Statistics for each of the four scenarios under stringent approach.*

Scenario	Valid counts [%]	Average Rainfall [mm]	Average Monthly Wind speed [m/s]
1	4	25	1.6
2	9	162	2.9
3	13	9	1.7
4	17	36	2.2

Discussion

Of the two approaches considered, the stringent approach provides, in the opinion of the author, more telling information on the potential effect of rainfall, or the absence of rainfall on dustfall rates. As such, the discussion will be focused on the results provided in Table 5. It is important to note that this approach excluded 57% of the total dataset, due to the stringent criteria of inclusion. In spite of this, the objective was to identify broad trends that could be used to guide further research into this topic.

The presence of rainfall on dustfall rates

The ability of rainfall to reduce dustfall rates is investigated based on Scenario 1 (above average rainfall and below average dustfall) and Scenario 2 (above average rainfall and above average dustfall).

Scenario 1 occurred during May 2013 only, which equates to 4% of the time. Typical rainfall during May is approximately 19 mm. Scenario 1 recorded 25 mm of rainfall, which is not substantially higher than the average. This rainfall occurred of a 2-day period. During the same period however, the average monthly wind speeds of 1.6 m/s is the lowest compared to all scenarios. It is unlikely that the above average rainfall that occurred during Scenario 1 would have resulted in reduced dustfall. There is a much greater likelihood that the reduced wind speeds during this period, prevented above average dustfall to occur.

Scenario 2 occurred during two months (November and December 2013). The hypothesis of Scenario 2 is that even when rainfall is above average, dustfall rates are above average. The highest rainfall (162 mm) and the highest wind speeds (2.9 m/s) occurred during these two months. More than half of the days during this period experienced rainfall. The potential for dust entrainment should have been the lowest during this period, based on the likelihood of increased soil / dust cohesion. It is likely that due to the high wind speeds (compared to the other Scenarios), the potential mitigating effects of rainfall dissipated in favour of wind speeds. This finding is supported in wind a wind erosion study in the Free State Province conducted by Wiggs and Holmes (2011). This study supported the initial hypothesis of this study, that increased rainfall should reduce dustfall, however, during a period of high rainfall, the dustfall rates were observed to be the highest, dispelling this hypothesis.

The absence of rainfall on dustfall rates

Scenarios 3 and 4, which considered the impact of the absence of rainfall on dustfall results accounted for 30% of the dataset. The key hypothesis in relation to the absence of rainfall is that under conditions of low rainfall, it is expected that dustfall rates would be higher. This is considered in Scenario 3, which occurred over three months (April, June and July 2014. It is known that the winter periods, whilst they are the driest, are also some of the calmest periods during the year. As such, this hypothesis is not found to be true in this study either.

Alternatively, Scenario 4 occurred the most during this study, a total of four months out of 24 (January, June, July and September 2013). The anomaly in this scenario is the relatively high wind speeds, coupled with the absence of rainfall, still resulted in below average dustfall rates. This is again, contrary to expectations that higher dustfall rates should occur under dry, windy conditions.

Whilst Scenarios 3 and 4 did not conform to expectations, it does indicate that the absence of rainfall may have a greater influence on observed dustfall rates, than the presence of rainfall would have.

Is rainfall an effective dust suppression mechanism

Soil moisture is a critical factor in determining whether soil particles can be entrained (Tsai, Lee and Lin 2003). Material that has a gravimetric moisture content above 0.2% is considered extremely resistant to wind entrainment (McKenna-Neuman and Nickling 1989). Rainfall, depending on the duration and intensity, should theoretically, provide sufficient moisture to reduce the potential for entrainment.

Based on the four scenarios, the rainfall does not suggest that it has an impact on dustfall rates in this study area. It is likely that the absence of rainfall has a greater chance of enabling suitable conditions for increased dustfall; however, even under the presence of low average rainfall, below average dustfall occurs at a similar rate. As such, neither the presence of rainfall nor the absence of rainfall is conclusive in this study to determine whether dustfall rates will be increased or reduced. Additional environmental and / or operational factors may have a greater importance in determining high or low dustfall rates. Environmental factors include, wind gusts, evaporation, surface drying, surface disturbance, soil wetness and soil type (Négyesi et al. 2016; Tsai, Lee and Lin 2003; Wiggs, Baird and Atherton 2004). Operational factors could include, frequency of unpaved road usage, vehicle speeds, type of vehicle usage and additional dust suppression techniques (chemical applications and water spraying).

The low resolution of dustfall monitoring makes the interpretation and analysis of trends coarse. Higher resolution information (weekly or daily monitoring) may improve the understanding of the key factors that influence dustfall rates. Environmental conditions before and after rainfall events may provide an improved understanding of factors that contribute to higher or lower dustfall rates.

This study does suggest that dust mitigation measures should be conducted year-round and irrespective of the natural rainfall patterns. Adherence to this is likely to have a much greater impact on reducing dustfall rates compared to a reliance on natural dust suppression (rainfall).

The requirement to report rainfall in the National Dust Control Regulations (South Africa 2013) should be considered as supporting conditions other primary factors, such as wind speed, that could influence dustfall rates.

Careful consideration concerning causation effects should be taken. This study does not support that rainfall results in reduced dustfall. There is a greater likelihood that the absence of rainfall can cumulatively influence dustfall rates compared to the presence of rainfall.

The environmental factors that occur in between rainfall events are likely to have a much greater impact on dustfall results compared to the rainfall event itself. Under hot and / or windy conditions, the potential for evaporation is increased. Even under calm conditions, soil moisture content decreases sufficiently in approximately four hours becoming highly susceptible to entrainment (Tsai, Lee and Lin 2003). Furthermore, the soil types will react very differently to varying amounts of rainfall. These factors could, in a short-timespan, override the actual rainfall event by drying the soil to the point that dust entrainment can occur soon after rainfall events.

Conclusion

Rainfall has the ability to increase soil cohesion, which in turn, can reduce the potential for dust entrainment to occur. This study has attempted to improve the understanding of the potential for rainfall to reduce dustfall rates in a localised study area of Mpumalanga.

This study suggests that rainfall has little influence on reducing dustfall rates. Only 4% of the data (one month) supported the hypothesis that dustfall rates were below average when rainfall is above average. It is likely that wind speeds have a greater influence on dustfall rates, as higher wind speeds have the ability to entrain larger, greater mass particles, which will be deposited through gravitational settling.

Additional factors, such as the absence of rainfall, the intensity and frequency of rainfall, evaporation rates and local sources of pollution may influence dustfall rates more than rainfall. The environmental conditions that occur in between rainfall events may be of greater importance than the actual rainfall event.

The hypothesis that rainfall can act as a natural dust suppressant is not supported by this study in this specific location. Careful consideration should be taken on how rainfall is attributed causation effects on dustfall rates in reports.

Management of dustfall should be undertaken irrespective of rainfall events to ensure effective mitigation of dustfall.

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