Research Article

Frequency of Mine Dust Episodes and the Influence of Meteorological Parameters on the Witwatersrand Area, South Africa

Olusegun Oguntoke, Matthew E. Ojelede, and Harold J. Annegarn

Department of Geography, Environmental Management and Energy Studies, University of Johannesburg, P.O. Box 524, Auckland Park, 2006, South Africa

Correspondence should be addressed to Olusegun Oguntoke; oluseguno@uj.ac.za

Received 30 April 2013; Accepted 26 September 2013

Academic Editor: Dimitris G. Kaskaoutis

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Aeolian dispersal of dust from gold mine tailing storage facilities impacts negatively on amenities, human health, and the environment of the Witwatersrand region, South Africa. The present study adopted a multivariate analytical method to quantify the effect of specific meteorological parameters on dust fall emissions, monitored at 22 sites in the central Witwatersrand area. Using meteorological and dust fall data from 2001 to 2010, the relationships between weather and dust fallout deposition rates were explored across the sites at different seasons. Dust deposition rate varied among seasons, with spring months showing the highest levels and frequency. Atmospheric humidity had negative correlations ($r = -0.25$ – -0.59) with dust fall while wind speed showed positive correlations ($r = 0.28$ – 0.58) at the selected sites ($P < 0.05$). Sites with low influence of relative humidity had higher impact on wind speed. Mean relative humidity below 50% and mean wind speed above 4 m/s were predicted as critical levels for dust episodes incidence at sites that recorded “heavy” and “very heavy” dust fall. For environmental planning purposes, current mitigation measures should be manipulated in relation to levels of air humidity and wind speed for dust emission reduction, especially during spring.

1. Introduction

Pollution arising from tailing storage facilities (TSFs) which serve as depository for waste materials generated in gold mining process has been source of concern to communities situated in their precinct. In the Witwatersrand area, residents of communities located within the buffer zone of TSFs are particularly concerned about their frequent exposure to airborne particulate matter associated with wind erosion of TSFs. Such concern has drawn public attention owing to the perceived negative impacts of mine waste materials on the health and safety of local communities and the environment, at large. Apart from wind-blown dust pollution that characterizes mine sites, soil and water contamination, unstable slopes on dumps, use of explosives, and presence of radioactive materials are other sources of concern in the Witwatersrand area [1, 2].

Dustfall consists largely of coarse or settleable particulate matter ($>30\ \mu\text{m}$ diameter) which constitutes approximately 40 percent of dust from mine source materials. The remaining proportion consists of finer particulates, of which the concentration of PM_{10} ranges from 22–38 to 11–26 vol.% in recent and older slimes [3]. Specifically, settleable dust impairs visibility when it forms dust plumes while its deposition on fabrics, buildings, vehicles, and water tanks constitutes a nuisance [4]. The ongoing reprocessing of sand and slime tailings to finer materials for gold recovery is aggravating dust pollution and the consequent further deterioration of ambient air quality in the Witwatersrand area [5, 6]. Residents of affected communities in the Witwatersrand region often complained about nuisance resulting from dust deposition, which causes loss of property value, damaged factory machineries, and disease conditions.

Despite ongoing research to ascertain the health implications of tailings dust in the Witwatersrand region, previous studies have confirmed increased hospital admission, emergency room visit, and mortality among patients of respiratory ailments [7, 8]. Many epidemiological studies have linked levels of ambient particulate matter with a variety of human health problems such as silicosis, pneumoconiosis, and increased risk of tuberculosis, lung cancer, scleroderma, and systemic lupus erythematosus [9, 10]. Specifically, exposure to gold mine dust, that is, rich in silica, has been linked to the development of chronic bronchitis, emphysema, and air flow obstruction [11, 12].

There are quite a number of factors that influence dust pollution and dispersal in mining environment [13, 14]. Assessing the role of climate, Mishra and Shambhu [14] observed that dust generation varied significantly in the premonsoon, postmonsoon, and winter periods. Furthermore, Wallace and Ott [15] indicated that locations found downwind of mine sites experienced higher dust concentration than others upwind. According to Scorgie [16] and Annegarn and Sithole [17], spring months are identified as critical periods of dust storm episodes in the Witwatersrand region. Taking an overview of the severity of dust erosion from TSFs in the study area, weather events are identified as predominant determinant factors.

To date, policy measures for control of mining impacts in the study area are focused on the minimization and mitigation of wind-blown dust [18–20]. In the region, particle size distribution and characterization of mine dust have been investigated [1, 21, 22] in addition to impact of dust on aspects of the environment [23]. Nevertheless, the underlying factors of seasonal occurrence of dust episodes and the consequent community outcry have not been sufficiently explored. While environmental policy aimed at limiting levels of dustfall exists in South Africa and the mine operators strive to curtail dust emission from TSFs, dustfall exceedance is recurrent. The permissible limits of dustfall in residential and industrial areas are $\leq 600 \text{ mg/m}^2/\text{d}^{-1}$ and $\leq 1200 \text{ mg/m}^2/\text{d}^{-1}$, respectively. Exceedance of these levels by any mineral exploring company in South Africa is allowed only thrice a year but not in two sequential months [24]. While international limits for dustfall levels are rare, the relevant agencies in South Africa have tried to enforce the abovementioned limits in order to protect the populace.

The present study investigated the interactions between pattern of dustfall and specific meteorological parameters using a multivariate analytical method. In addition, it quantified the influence of meteorological parameters on the levels of wind-blown mine dust from gold TSFs in Witwatersrand area. A good understanding of the specific effects of meteorological factors on mine dust emission is capable of aiding optimal allocation of resources and intervention planning in residential areas.

2. Materials and Method

The Witwatersrand region is located in Gauteng province, the gold mining hub of South Africa. Gauteng province is located on high-altitude grassland called Highveld, about

1,500 m above mean sealevel. The climate is mostly influenced by subtropical weather systems. Even though the province is at subtropical latitude, the climate is comparatively cooler, especially in Johannesburg (1,700 m asl). Most precipitation occurs as brief afternoon thunderstorms; however, relative humidity never becomes uncomfortable. Winters are crisp and dry with frost occurring often in the southern areas. Snow is rare, but it has occurred on some occasions in the Johannesburg area [25].

At summer time especially January, average maximum and minimum temperature of Johannesburg are 26°C and 15°C while in winter (June) the average maximum and minimum temperature range between 16°C and 4°C . Annual precipitation in the city is approximately 713 mm. In Gauteng, summer days are warm and winter days are crisp, clear, and wind-free. There are about six weeks of cold weather in mid-winter (from July to August) and summer offers warm sunshine followed by balmy nights (from October to March). The rainy season is in summer rather than winter (June–August). Rainstorms are often harsh accompanied by much thunder and lightning and occasional hail, but they are brief and followed by warm sunshine [25].

The study utilized data from two sources: data on dustfall monitored from 2001 to 2010 (Annegarn Environmental Research, now SGS) and meteorological data for the same period (from the South Africa Weather Service). Dustfall data were collected from Crown-Gold dust monitoring project (CRUST) in Johannesburg. The bucket collection technique adopted by CRUST for dustfall monitoring follows the American Society for Testing and Materials (ASTM D1739) [26]. The buckets, left on site for $30 (\pm 3)$ days for dust collection, are partly filled with distilled water, to which a biocide is added to prevent the growth of algae. In the laboratory, the collected and preserved sample is filtered, dried, and weighed. The dustfall rate (D) is determined by using the formulae

$$D = \frac{W}{A} \left(\text{mg/m}^2/30 \right), \quad (1)$$

where W stands for mass of dust collected and A is the area of the container used.

In the study area dustfall monitoring sites were grouped into nine zones, namely, Crown, City Deep, Heriotdale, Western, Fleurhof, Soweto, Robinson, Knights, and Mennel. Sites were randomly selected from eight zones with the exclusion of Mennel, where dust monitoring commenced only in 2005. In all, 12 residential and 10 nonresidential sites were selected as follows: Crown area (3 sites), City Deep area (2 sites), Heriotdale area (5 sites), Western area (2 sites), Fleurhof area (2 sites), Robinson area (2 sites), Soweto area (3 sites), and Knights area (3 sites); see Figure 1. The detailed description of the index numbers (codes) of the selected locations is presented in Table 4.

The meteorological data for OR Tambo International airport, which is the nearest weather station to the study area with complete daily records for 2001–2010, were used. Weather data on rainfall, air humidity (%), temperature ($^\circ\text{C}$), air pressure, wind speed (m/s), and wind direction were retrieved from the agency. Minimum, maximum, and mean values of these parameters were computed on monthly

FIGURE 1: Location of selected dust monitoring sites in the Witwatersrand region.

basis and used as explanatory variables in correlation and regression analyses.

Dust data were analysed for seasonal patterns using Box and Whisker graphical presentation. Moreover, correlation analysis was employed to investigate the relationship between meteorological parameters and dustfall at each of the monitoring sites. In order to examine the contribution of meteorological parameters to dustfall levels, stepwise regression model was used. Based on the computation of mean, minimum, and maximum values for each of the six meteorological parameters, 18 parameters were generated. Employing these parameters in correlation analysis revealed that only 10 of them have significant correlation with dustfall at any of the sites. Furthermore, the 10 significant meteorological parameters were subjected to colinearity diagnostic test in order to make them fit for regression analysis. Two variables (mean pressure and maximum temperature) that failed the test ($r \geq 0.91$) were also excluded from the regression analysis. Out of the eight parameters that were presented in the correlation analysis, only five had significant determination coefficients in the regression analysis.

The regression model is of the form

$$Y = a + b_1 X_1 + b_2 X_2 + b_3 X_3 \cdots b_n X_n, \quad (2)$$

where a stands for the intercept of model slope and b_1 – b_n are the quotients of the explanatory variables. The dustfall level at each site (dependent variables) was regressed on eight meteorological parameters (predictor variables) using stepwise option. All statistical tests were conducted using

the statistical package for the Social Sciences (SPSS version 20) and the results considered significant at $P \leq 0.05$ [27].

3. Results

The mean dust levels during summer were generally below the $600 \text{ mg/m}^2/\text{d}$ limit for residential areas, although higher values (700 – $1,600 \text{ mg/m}^2/\text{d}$) were recorded at 8JCCH, 57JCECL, and 50MOLLO (Crown, Robinson, and Soweto zones) on some occasions (Figure 2(a)). In nonresidential locations, mean dust levels were also below $1,200 \text{ mg/m}^2/\text{d}$ set for nonresidential environment (Figure 2(e)). Notwithstanding, 23IMP and 65KG MIN locations (Heriotdale and Knights zones) recorded dust emission between $2,500$ and $3,500 \text{ mg/m}^2/\text{d}$ sometimes.

In autumn, mean dustfall monitored at residential and nonresidential sites was within the permissible limits. Notable exceedance among residential areas was observed at 8JCCH (Crown zone) ($>1,600 \text{ mg/m}^2/\text{d}$). Similarly, two nonresidential sites, 65KG MIN and 27PP (Knights and Heriotdale zones), recorded between $1,400$ and $2,000 \text{ mg/m}^2/\text{d}$ (Figures 2(b) and 2(f)) on few occasions.

At winter, mean dust levels were generally low at the selected residential sites (143 – $462 \text{ mg/m}^2/\text{d}$). Nevertheless, 8JCCH, 34NENT, and 47CHIA (Crown, Western, and Soweto zones) recorded high dust levels between $1,000$ and $2,300 \text{ mg/m}^2/\text{d}$ on some occasions. Three residential sites (23IMP, 27PP, and 65KG MIN; Heriotdale and Knights zones) equally recorded high dust levels ranging from $1,800$ to $2,400 \text{ mg/m}^2/\text{d}$ occasionally (Figure 2(e)).

FIGURE 2: Seasonal pattern of dust levels in residential ((a)–(d)) and nonresidential ((e)–(h)) areas.

TABLE 1: Correlation between dust levels at selected sites and meteorological parameters.

Sample site	Mean rain	Max rain	Min temp	Mean speed	Max speed	Mean direc	Mean hum	Min press
Residential location								
4EDRF	-0.27**	-0.30**	-0.24*	0.31**	0.31**	0.23*	-0.44**	-0.21*
8JCCH	-0.17	-0.15	-0.13	0.06	0.16	0.11	-0.09	-0.18
61SKL	-0.27**	-0.25**	-0.20*	0.38**	0.28**	0.25**	-0.51**	-0.11
34NENT	-0.20*	-0.17	-0.16	0.41**	0.37**	0.19*	-0.38**	-0.21*
40HOSTEL	-0.02	-0.05	-0.02	0.58**	0.37**	0.23*	-0.28**	-0.22*
43MLTB	-0.18	-0.21*	-0.08	0.31**	0.32**	0.09	-0.39**	0.17
47CHIA	-0.35**	-0.35**	-0.28**	0.47**	0.43**	0.32**	-0.59**	-0.23*
50MOLLO	-0.22*	-0.23*	-0.15	0.52**	0.40**	0.17	-0.40**	-0.19*
53-1121	-0.12	-0.07	-0.21*	0.27**	0.31**	0.15	-0.33**	-0.14
57JCELC	-0.13	-0.14	-0.13	0.39**	0.29**	0.25**	-0.36**	-0.08
59JCDOG	-0.23*	-0.26**	-0.16	0.35**	0.24**	0.26**	-0.44**	-0.13
70CTC	-0.17	-0.17	-0.12	0.28**	0.27**	0.15	-0.42**	-0.12
Nonresidential locations								
13ILLA	0.04	0.04	0.11	0.17	0.01	-0.04	0.14	-0.12
15ILLG	-0.18	-0.23*	-0.02	0.47**	0.40**	0.10	-0.39**	-0.22*
18BTH	-0.28**	-0.28**	-0.19*	0.43**	0.33**	0.18	-0.46**	-0.23*
21HR	-0.16	-0.10	-0.05	0.47**	0.33**	0.30**	-0.38**	-0.17
23IMP	-0.15	-0.13	-0.06	0.47**	0.29**	0.29**	-0.37**	-0.10
27PP	-0.18	-0.16	-0.18	0.30**	0.30**	0.29**	-0.34**	-0.11
32KLL	-0.32**	-0.29**	-0.31**	0.41**	0.40**	0.29**	-0.52**	-0.17
45WAYN	-0.23*	-0.23*	-0.12	0.47**	0.38**	0.06	-0.46**	-0.23*
65KG MINING	-0.13	-0.13	-0.07	0.40**	0.25**	0.18	-0.29**	-0.10
66WDSS	-0.19	-0.17	-0.17	0.34**	0.27**	0.08	-0.32**	-0.14

*95% confidence level.

Mean rain: mean rainfall.

Min temp: minimum temperature.

Max speed: maximum wind speed.

Mean hum: mean air humidity.

**99% confidence level.

Max rain: maximum rainfall.

Mean speed: mean wind speed.

Mean direc: mean wind direction.

Min press: minimum air pressure.

The mean dustfall values were highest at all sites during spring. For instance, the mean values monitored at 40HOSTEL and 50MOLLO sites were higher than those monitored at 40HOSTEL and 50MOLLO sites that were higher than the limit set for residential areas (Figure 2(d)). While two of the sites did not record any exceedance during the study period, six sites had values well above the limits (1,120–2,270 mg/m²/d) occasionally. Among the selected nonresidential sites, mean dust levels were higher than the permissible limit at 23IMP and 65KG MIN (1,500–2,500 mg/m²/d) locations. Sometimes, dust levels reached between 4,200 and 28,700 mg/m²/d at 21HR, 23IMP, 27PP, and 65KG MIN sites (Heriotdale and Knights zones) as shown in Figure 2(h).

It was observed that dust episodes experienced at 8JCCH occurred in the earlier years of the study period (2002 and 2003). Moreover, locations such as 47CHIA, 27PP, and 57JCELC recorded high dust levels in one or two months within a year of the study period. At 50MOLLO, 23IMP, 21HR, 65KG MIN, and 34NENT, the observed dust episodes

occurred more frequently between 2005 and 2010. The incident dust episodes in the aforementioned five locations can be adduced to the reprocessing of old and stabilized mine dumps for fine gold extraction. Generally, all sites portrayed a similar monthly pattern of asymmetrical shape curve with relatively low dustfall from December, January to July while August to November recorded high dustfall. Across the seasons, monitored dust levels were of the order: spring > winter > summer > autumn during the study period. This observed pattern is not coincidental but an indication of seasons' influence on dustfall, as the data presented spanned a period of 10 years.

The mean monthly rainfall showed negative correlation with dustfall levels in residential and nonresidential sites (Table 1). The correlation coefficient ranged between (r) -0.19 and -0.35 ($P < 0.05$); 66WDSS had the least while 47CHIA had the highest. Other meteorological parameters that showed negative association with dust level included minimum monthly temperature ($r = -0.19$ – 0.31), mean

TABLE 2: Determination of dust fall levels by meteorological parameters at selected sites.

Sample sites	Wind speed	Humidity	Others	Total %
Residential location				
4EDRF	—	0.19	0.06	25.0
61SKL	0.07	0.26	0.03	36.9
34NENT	0.17	0.09	—	25.9
40HOSTEL	0.34	0.03	0.03	39.0
43MLTB	0.04	0.15	0.15	34.3
47CHIA	0.12	0.35	0.03	49.7
50MOLLO	0.28	0.08	0.03	38.8
531121	—	0.11	0.09	19.4
57JCELC	0.15	0.08	—	23.7
59JCD OG	0.07	0.19	—	26.1
70CTC	0.07	0.17	—	24.0
Nonresidential locations				
15ILLG	0.22	0.09	0.06	35.9
18BTH	0.11	0.21	0.03	35.0
21HR	0.22	0.08	—	29.9
23IMP	0.22	0.08	—	29.4
27PP	0.06	0.11	—	17.1
32KLL	0.10	0.27	—	36.9
45WAYN	0.22	0.13	0.10	45.5
65KG MIN	0.16	0.04	—	20.1
66WDSS	0.11	0.06	0.03	20.7

monthly humidity ($r = -0.28-0.59$), and minimum monthly pressure ($r = -0.19-0.23$).

At residential and nonresidential sites, dustfall levels had positive correlations with mean wind speed and mean wind direction. Among the selected areas, the correlation between mean wind speed and dust levels ranged from (r) 0.27 to 0.58 at 53–1121 and 40HOSTEL sites, respectively. Mean wind direction and dustfall levels showed correlation coefficient that ranged from (r) 0.23 to 0.32 (4EDRF and 47CHIA sites) in residential and nonresidential areas.

There was no significant association between all the meteorological parameters and dustfall at 8JCCH (Crown zone) and 13ILLA (City Deep) sites. The inability of meteorological parameters to explain dustfall levels at these locations points to overriding influence of factors other than meteorological parameters.

The two significant meteorological parameters that explained dustfall pattern in the study area were mean wind speed and mean relative humidity (Table 2). Other parameters that showed low but significant influence on dustfall at a few locations included mean wind direction and minimum air pressure. The determination coefficients of regressing dustfall on mean wind speed ranged from (R^2) 0.04 to 0.34 (4%–34%). Mean wind speed did not explain dustfall levels at 4EDRF and 53–1121 sites throughout the study period. The influence of this meteorological parameter was less than 10% ($R^2 = 0.1$) at each of 61SKL, 43MLTB, 55CDOG, 70CTC (residential areas), and 27PP (nonresidential areas) sites. At 50MOLLO and 40HOSTEL (residential areas), 15ILLG,

21HR, 23IMP, and 45WAYN (nonresidential areas) sites, the mean wind speed explained more than 20% of dustfall levels.

The mean relative humidity was the second meteorological parameter that had significant influence on dustfall levels. At 61SKL, 47CHIA (residential areas), 18BTH, and 32KLL (nonresidential areas) sites, mean relative humidity explained between 21% and 35% ($R^2 = 0.21-0.35$) of the dustfall levels. At four residential sites and five nonresidential sites, the determination coefficients of relative humidity were less than (R^2) 0.10.

It was observed that the influence of mean wind speed and mean relative humidity was contrasting at most sites. In addition, each of the other meteorological parameters that showed significant explanation of dustfall levels was less than 10% ($R^2 = 0.10$) at the sites. The aggregate influence of the significant meteorological parameters was highest at 40HOSTEL, 50MOLLO, 47CHIA (residential areas), and 45WAYN (nonresidential area) sites within the study period. Since meteorological parameters did not explain more than 50% of dustfall levels at any site in the study area, other factors were responsible for the unexplained percentage.

In order to determine the levels of mean wind speed and mean relative humidity that generated dust episodes (high levels) in residential and nonresidential sites, regression equations were employed. The six residential sites that recorded dust level above 600 mg/m²/d (34NENT, 40HOSTEL, 50MOLLO, 53–1121, 57JCELC, and 70CTC) in addition to four nonresidential sites that had dust levels above

TABLE 3: Determination of dust fall levels by meteorological parameters.

Site code	Regression equation		β value	R	R^2 (%)	Critical level
34NENT	$Y_{df} = 151.3X_{ws} - 339.28$	Model 1	150.0	0.41	17	>4 m/s (ws)
40HOSTEL	$Y_{df} = 233.3X_{ws} - 618.93$	Model 2	235.7	0.58	34	>4 m/s (ws)
50MOLLO	$Y_{df} = 209.2X_{ws} - 479.45$	Model 3	217.8	0.52	25	>4 m/s (ws)
53-1121	$Y_{df} = -6.4X_{rh} + 570.27$	Model 4	-6.35	0.33	11	<60% (rh)
57JCELC	$Y_{df} = 158.1X_{ws} - 336.67$	Model 5	158.1	0.39	15	>4 m/s (ws)
70CTC	$Y_{df} = -4.4X_{rh} + 526.57$	Model 6	-4.41	0.35	17	<50% (rh)
21HR	$Y_{df} = 314.0X_{ws} - 803.97$	Model 7	314.9	0.47	22	>4 m/s (ws)
23IMP	$Y_{df} = 410.8X_{ws} - 1105$	Model 8	401.2	0.47	22	>4 m/s (ws)
27PP	$Y_{df} = 7.0X_{ws} - 661.96$	Model 9	-7.22	0.34	11	<60% (rh)
32KLL	$Y_{df} = -9.1X_{rh} - 148.32$	Model 10	-9.13	0.52	15	>4 m/s (ws)
65KG MIN	$Y_{df} = 406.7X_{ws} - 678.37$	Model 11	406.7	0.40	16	>4 m/s (ws)

Models are significant at $P < 0.01$.

df: dustfall; ws: mean wind speed, rh: mean relative humidity.

TABLE 4: Description of the selected sites in the Witwatersrand region.

S/n	Site code	Site name	Site description	Locality/area
1	4EDRF	Edgars roof	Residential	Crown
2	8JCCH	Joburg city council house	Residential	Crown
3	61SKL	Stockwell	Residential	Crown
4	13ILLA	Illman A	Industrial	City Deep
5	15ILLG	Illman gate	Industrial	City Deep
6	18BTH	Baumont truck hire	Industrial	Heriotdale
7	21HR	Haggie rand	Industrial	Heriotdale
8	23IMR	Impala motor repairs	Industrial	Heriotdale
9	27PP	Pick'n pay	Industrial	Heriotdale
10	32KLL	Klem Lloyd Li	Industrial	Heriotdale
11	34NENT	Nasrec entrance	Residential	Western
12	40HOSTEL	Shaft 17 (hostel)	Residential	Western
13	43MLTB	MedLife TB hospital	Residential	Fleurhof
14	5WAYN	Wayne plastics	Industrial	Fleurhof
15	47CHIA	Chiawelo clinic	Residential	Soweto
16	50MOLLO	Mollo house Diepkloof east	Residential	Soweto
17	53 1121	Matswee house 1121	Residential	Soweto
18	57JCELC	Joburg electricity Department	Residential	Robinson Deep
19	59JCD OG	Joburg dog training centre	Residential	Robinson Deep
20	65KG MINING	Knights Gold mine	Industrial	Knights
21	66WDSS	Wit Deep sand and stone	Industrial	Knights
22	70CTC	Continental China	Residential	Knights

1,200 mg/m²/d guideline (21HR, 23IMP, 27PP, and 65KG MIN) were used as a case study.

From the graphical plotting of regression models presented in Table 3, mean wind speed higher than 4 m/s yielded dust levels well above 600 mg/m²/d at 34NENT, 40HOSTEL, 50MOLLO, 57JCELC, 21HR, 23IMP, and 65KG MIN sites. At 53-1121, 70CTC, and 27PP sites "heavy" dustfall was predicted at mean relative humidity of less than 50%. The application of these predictions to the current dust emission will be based on the assumption that other meteorological and anthropogenic conditions have not changed from the pattern observed during the study period.

4. Discussion

Using monthly dustfall data over the period of 10 years in this study, there were variations in dustfall levels among the selected monitoring sites with two sites in Heriotdale zone recording the highest levels. The observed variation among sites may not be unconnected with the distance of locations to nearest tailing facilities, effectiveness of dust abatement measures, and presence of ownerless (uncontrolled) dump in the area, movement of earth materials, and the scale of mining operations. GDARD report [28] indicated similar variations in the level of dustfall among monitoring sites in

Gauteng province. In related studies, Petrilli [29] and Mishra and Shambhu [14] reported spatial variations in dustfall.

The general low dustfall in autumn, winter, and summer and the high concentration in spring indicate seasonality of dust emission in the study area. Summer, for instance, is characterized by high wind speed but its erosive effect is attenuated by heavy rainfall and strong vertical air mixing; hence low dust erosion and dispersion. Again, autumn is characterized by low speed winds, intermittent rainfalls, and minimal convective activities which produce low dust emission. Although winter months are dry, implying the availability of erodible materials, low speed of the prevailing wind systems yields minimal dust emission and deposition.

Conversely, the high dustfall emission during spring season could be attributed to relatively high wind speed and low rainfall, which are characteristic of the season [25]. Specifically, the highest dustfall recorded by virtually all sites during spring months was attributable to both factors of high erosivity potential of prevailing wind and high erodibility of loose and dry dust. Supporting the observed seasonal pattern of dustfall in the study area, Annegarn and Sithole [17] and Annegarn et al. [1] indicated the spring season as the “high dust period” in the Witwatersrand region. According to Fukagawa et al. [30], atmospheric aerosol portrayed distinct seasonal pattern in Japan. Specifically, the characteristics of wind speed, humidity, and precipitation in each season were shown to influence dust emission [31].

Both mean relative humidity and mean rainfall showed significant negative association with dust fall levels in the Witwatersrand area similar to the findings of Naddafi et al. [32]. Generally, high relative air moisture provides water film that binds dust particles thereby reducing dust erodibility by wind [33, 34]. Moreover, high moisture content in atmospheric air constitutes additional load carried by wind, hence reducing its speed and erosivity. In Kathmandu valley (India), Giri et al. [35] reported negative correlation between increase of rainfall and humidity with average PM_{10} emission.

Furthermore, the higher negative correlation between mean relative humidity and dust level than mean rainfall may point to higher impact of moisture in the air than rainfall incidence which is evidently periodic and discontinuous. In agreement with this finding, Petrilli [29] indicated that air humidity was responsible for higher percentage of dustfall variations compared to rainfall.

The positive association between wind speed and dustfall in this study concurs with the inverse relationship between amount of dustfall and wind speed reported by Naddafi et al. [32]. Generally, winds with speed above the threshold for a given particle size are capable of eroding and transporting dust over distance [36], provided other conditions are supportive. High wind speed, therefore, implies high erosion potential for dust emission [37].

Variations in dustfall levels were explained largely by mean relative humidity, mean wind speed, and maximum temperature. According to similar analysis conducted by Yassen [38], rainfall, relative humidity, wind speed, and temperature explained 46% of dustfall in Kuala Lumpur (Malaysia). Other factors such as the type of equipment

used, topography of the area, vegetal cover, brittleness and hardness of the materials, and speed and frequency of transport equipment [13, 14] could account for the remaining percentage of dustfall variations.

The levels of dustfall at two sites which showed no relationship with meteorological parameters indicated the influence of factors other than meteorology. Such factors could include construction work within the vicinity of the areas, spontaneous dust emission due to equipment failure, and reprocessing of stabilized TSFs for fine gold extraction.

The prediction of 4 m/s and above as wind speed that produced dust episode in this study is akin to 16 km/h remarked by Annegarn et al. [1] as wind speed required for dust lifting in the study area. Lee and Tchakerian [39] predicted a higher wind speed of 6 m/s for initiating blowing dust in the Southern High Plains of the United States. The disparity in wind speed predicted by these authors was due to the difference in the type of earth materials that were studied.

5. Conclusion

Aeolian dust from TSFs in the Witwatersrand area varied among the sites and across the seasons. The two most significant parameters that influenced dustfall at most sites in the study area were mean relative humidity and mean wind speed. While mean humidity showed negative correlation, the mean wind speed was positive. Although the coefficient of determination derived from regression analysis revealed differences in percentage contribution of the four significant meteorological parameters, sites with low impact of mean humidity had relatively higher percentage contribution of mean wind speed. Critical levels of mean humidity and mean wind speed that yielded dust episodes were predicted at selected sites.

For environmental planning purposes, current mitigation measures should be manipulated in relation to levels of air humidity and wind speed especially at spring months for dust emission reduction. Moreover, with meteorological parameters explaining about half the pattern of dustfall, there are other factors that contributed to the occurrence of dust episodes in the Witwatersrand region. A more effective dust mitigation measures and community adaptation training should be introduced in residential areas that receive high dust emissions from TSFs. Finally, network of mobile weather stations that could provide early warning signals based on wind speed and air humidity data should be installed within the residential areas that experience frequent dust episodes.

Acknowledgments

The authors appreciate the South African Meteorological Agency and Crown-Gold Dust Monitoring Project (CRUST) for data provision.

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