Evaluation of Dust Fallout at Malmberget mine, Sweden for the period August 2009 to August 2010
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ABSTRACT
Dust is produced when mining operations take place. The transportation and deposition of dust depend mainly on climatic factors, as well as land surface characteristics. Malmberget mine operated by Luossavaara-Kiirunavaara Aktiebolag is one of the most important iron mines in Sweden. The mining area includes an area with a huge open pit and an industrial center. Both sites are surrounded by residential areas where people are suffering from dust problems. The collected dust from 26 measuring stations during the period 2001 to 2010 has been analyzed using the surfer 9.0 program. Generally speaking the dust fallout in summer was higher than that in winter and the volumes decreased through time as a result of implemented dust control methods. Analysis of the data from August 2009 to August 2010 indentified two sources of dust generation. One was located close to the open pit, and the other near the current mining industrial center. Among all the measuring stations, the maximum and minimum values within the year were 1284 g/100m²/30d and 9 g/100m²/30d, respectively. Dust production around the Malmberget mine was attributed to three reasons, namely, wind erosion of the exposed area close to the open pit, truck transportation on haul roads, and active stockpiles. In addition to climatic factors, the variation of dust detected depended on mining activities and road construction.

Keyword: Dust, Dust fallout, Malmberget mine, Wind erosion, Haul road, Stockpiles

1. Introduction

Wind erosion of soils is greatly contributing to the global dust and 20-50 % of that is derived from human-disturbed soils (Shao, 2008). Dust is produced when mining operations take place, and the possible sources are blasting, overburden removal, shovel and truck loading, haul roads, truck dumping, conveyor transfer points, waste disposal and land reclamation (Lyle et al. 1983). The wind erosion rate over human-distributed soils can be many times higher than that over natural soils. Chepil (1950a, 1950b, 1951a, 1951b, 1951c) has studied the properties of soil, which influence soil erosion, and summarized several relations between erodibility of soil by wind and apparent density of soils, and state of dry aggregate. Gillette et al. (1972) computed vertical aerosol fluxes near ground in an eroding field by assuming a vertical transport mechanism similar to that for momentum. Shao (2008) elaborated dust mission, transportation and deposition due to wind erosion, introduced measuring techniques, as well as explained integrated wind-erosion modeling for estimation.
Mining activities generate and transport dust particles to the neighborhood according to particle sizes and wind speeds. Depending on the speed of the wind particles larger than 10 μm can be suspended in the air for long distances or deposited short distances within the vicinity of the source area. On the other hand, particles smaller than 10 μm are usually suspended in the air for a relatively long period of time. The amount of dust generated largely depends on the activities exerted on the surface during mining. Both the type of the machinery working and the magnitude of the mineral operation decide how much dust is generated. The transportation, distribution and deposition of dust depend mainly on wind velocity, wind turbulence, direction, air humidity, and precipitation. However, wind velocity and wind turbulence are influenced by surface roughness, which is a matter of the ground surface characteristics of the mining site due to variety of mining operations. Dust concentration is used to monitor the ambient air conditions of a mining site, and its value therefore has a close relationship with the mining operations. It is believed that vehicle haul road interaction is the most effective dust source among all the dust generation activities in mining area.

The United States Environmental Protection Agency (U.S. EPA, 1998) has reported that haul trucks generate the majority of dust emissions from surface mining sites, accounting for approximately 78%-97% of total dust emissions. Muleski and Cowherd (1987) estimated 70 percent of total dust from surface coal mines was produced by trucks traveling on haul roads. Cowherd et al. (1979) estimated that about 50% of the total dust released during dumper traveling on unpaved roads and 25% for both loading and unloading. Jutze (1976) also estimated fugitive dust from mining operations, and although the values differ it confirmed that truck driving on haul roads is the most effective dust generation activity. Fugitive dust emissions from stockpile have brought many ecological and economical problems. Many authors have pointed out the possible effect of pile topography on the dust production pattern (Borges and Viegas, 1988; Wang et al., 1990; Badr and Harion, 2007).

In this paper, the general variation of the dust levels from 2006 to 2010 in Malmberget mine in Sweden are analyzed, with more detailed analysis on the dust fallout during the year August 2009 to August 2010. The result showed the yearly and monthly variation and distribution of dust. The most effective sources of dust production have been pin-pointed and possible recommendations are presented.

2. Materials and methods

Malmberg mine operated by Luossavaara-Kirunavaara Aktiebolag (LKAB) is one of the most important iron mines in Sweden. It is located at Gällivare, 75km from Kiruna, and contains some 20 orebodies as shown in Fig.1. The mine covers a huge area spreading over approximately 5km from east to west and 2.5 km from north to south. Mining began in 1892, since then over 350Mt of ore had been extracted. In 2006, it produced around one-third of LKAB’s total production of 23.3Mt of iron-ore products (Mining-technology.com, 2010). Surface open pit mining method was firstly used to reach and exploit the ore minerals.
A huge depression (fig. 2(a)) was abandoned after the finished surface open pit mining, and then large-scale sub-level caving became the predominant mining technology at Malmberget.

The land surface features have been deformed due to the underground mining. The surface soil is prone to wind erosion in this bare area after mining. Those who are still living in Malmberg and the vicinity complain about elevated dust level due to mining activities. The movement of trucks from the industrial area to dump the debris into the pit (Fig. 2a) enhanced dust generation as shown in Fig.2b.

However, due to some security reasons the filling of the pit was discontinued in March 2009. The LKAB industrial center is now located northeast to the open pit. Sub-caving mining activities take place in this area and the main mining operation area includes a haul
area with stockpile in use, product stockpile area and sedimentation reservoir for used process water as in Fig. 3. There are residential areas located both around the open pit and nearby the LKAB industrial center.

![Fig. 3. Main operation areas in Malmberget mine (from LKAB)](image)

The mining company installed a series of dust deposit collectors to measure the dust fallout over the area (fig. 4). The dust fallout collector is produced by the Norwegian Institute for Air Research (NILU) as shown in Fig. 5.

![Fig. 4. Locations for Dust fallout measuring stations (red dots) in Malmberget mine](image)
International Standardization Organization (ISO) has considered the collector for adoption as an international reference collector for particulate fallout. The mounting stand is adjustable in height. The collection and weighing of the material was done on approximately monthly bases and reported as g/100m$^2$/30day. The systematic data recording started since 2001 but no meteorological monitoring was installed on site.

Analysis of the data was done using Surfer 9.0 program. This is a contouring and 3D surface mapping program that runs under Microsoft Windows. It can quickly and easily convert data into many types of output including contour, 3D surface, 3D wire frame, vector, image, shaded relief, and post maps.

3. Results and Discussion

The general trend of variation of dust level on the mining site from 2001 to 2010 is shown in Fig.6 and Fig.7. The yearly average (from August till July the year after) dust fallout is shown in Fig.6. The winter average and the summer average of dust fallout were also calculated and shown in the figure. April, May, June, July and August were considered as summer time and the rest of the months were considered as winter time. Generally speaking the amount of dust fallout was decreasing with time because of some implemented dust
control methods such as watering the stockpiles and the haul roads. The slight increase of dust fallout during the year 2009 and 2010 was due to a road construction near the open pit area. More dust was produced by mining activities during summer than winter due to the fact the climate in the summer was sometimes very windy and dry, while the most of the surfaces were covered by snow during the winter.

![Fig.6. Yearly average, winter average and summer average of dust fallout](image)

![Fig.7. Monthly average of dust fallout during the year 2006 till 2010](image)
Fig. 7 shows the calculated monthly average of dust fallout from 2001 to 2009. The peak value was 265 g/100 m²/30 d appeared in May, 2007, and the lowest dust fallout was 25 g/100 m²/30 d in August, 2009. The general trend shows a distinct increase of dust fallout in April and May. Since mining activities were at a constant level, the change of the amount of dust fallout should be attributed to the local weather conditions. April and May were most effective months in dust production because of windy weather in early spring. Though, it is very windy in April, the surfaces were still partly covered by snow. May is the most effective month for dust production due to the fully exposed surfaces and the strong windy weather. Dust fallout in June, July and August were relatively low because of intensive rainfall in summer.

The detail of the dust fallout during the year August 2009 to August 2010 was analyzed using Surfer 9.0 program for the mining area as shown on the contour maps in fig. 9. The contour mapping area corresponds to the map area in fig. 8. Two sources of dust generation were identified. The first was the open pit (A), and the second was the current mining industrial center (B) (Fig. 8). The relative significance of the two sources was changing with time. Though, the industrial center acted as the dominate source for most of the time. Among all the measuring stations through the year, the maximum and the minimum value were 1284 g/100 m²/30 d (station 35, May 2010, Fig. 4) and 9 g/100 m²/30 d (station 22, December 2009, Fig. 4) respectively. Both stations were close to the open pit. The difference between the maximum value and the minimum value was huge, and the amount of dust fallout varies though the year depending on the weather conditions.

Fig.8. Source A, Source B and cross section line
Fig. 9. Map of the test area and contour lines for dust fallout from August 2009 to August 2010. (The contour lines were made according to those days when data were available, and the date is shown below each individual figure. The color scale is shown on the top to the right.)
Fig. 10. Dust mass along the cross section passing through source A and source B.
In order to visualize the change through the year, the variation of dust fallout along a cross section (the red line in Fig. 8) which passes through both source A and source B is presented in Fig. 10. Y-axis stands for the dust mass in g/100m²/30day, and X-axis is the horizontal length along the cross section line shown in Fig. 4. One remark is that the limitation of the curves was set to be 400 g/100m²/30d as most of the peak values were less than 400 g/100m²/30d. Dust generation from source A was attributed to wind erosion of the exposed areas near the open pit. Source B was the LKAB industrial center where sub-caving underground mining activities took place, and the haul roads and the active stockpiles were suspected as dust sources. However, the peak value in May 2010 was far beyond the limit of Fig. 10.

If there was no drastic change in the weather condition at that time, it appears some special activities had taken place to produce the dramatic peak value on dust fallout. The two source areas (A and B) more or less had the same dust fallout during August and September 2009 as well as March and April 2010 (Black color in Fig. 10). Area A, however, had higher dust fallout values relative to area B during May and June 2010 (green color in Fig. 10). The reverse was true during November and December 2009 and January, February and July 2010 (red color in Fig. 10). This means that in May and June 2010, source A was contributing most of the dust. In November and December 2009, January, February and July 2010, source B was the main dust contributor.

The remainder of the investigated months both sources were contributing more or less equivalent amounts of dust. Nevertheless the values were higher during March and April in 2010 than the other months. The dust distribution curves along cross section AB generally indicate that the dust concentrations were high at the pit and industrial areas which confirms the result from Fig. 9.

Total dust fallout on the entire area was calculated and shown in Table 1. In addition to the two dust sources identified, the total mass was also calculated for the sub-areas A, B and C (Fig. 11) around both sources. These areas were the residential areas where people are very concerned of air quality.

Fig. 11 outlines the sub-areas A, B and C. The areas covered are 7.7km², 6.5km², 4.8km² respectively. Total of investigation area is 51 km². Table 1 shows that, for the entire area, the highest total dust fallout of 60.1t/30d was recognized in May 2010 and the lowest value of 17.8t/30d was noted in December 2009. The peak total dust fallout on Area A and Area B were 15.6t/30d in May 2010 and 11.8t/30d in March 2010, respectively. The value for Area C was comparatively low, and the highest and the lowest figure were 7.4t/30d in May 2010 and 0.9t/30d in January 2010 respectively. The highest value in Area C appeared at the same time as the highest total dust fallout on the entire area took place, and source A was dominating in dust production at that time. The unit masses for each area are plotted in Fig. 12. The shifting significance of two sources is clearly visualized. A conclusion could be drawn that source B was in fact dominating in dust production for most of the time, though source A gave the peak dust production in May 2010.
The area divided into three sub areas A-open pit, B-industrial center and C-residential area

The Area C (marked yellowing in Fig. 12) showed the lower dust values compared to areas A and B because it is more distant from the mining activities. In May in 2010, however, the dust in Area C was higher than that in Area B and less than that in Area A. This was probably because the wind was from northeast and with the dominating dust production in Area A, the dust plume traveled to Area C. The red bar represents the average dust fallout over the whole area.

Table 1: Total dust mass and unit mass on area A, B, C and on the entire area

<table>
<thead>
<tr>
<th>Date</th>
<th>Area A 7.7km²</th>
<th>Area B 6.5km²</th>
<th>Area C 4.8km²</th>
<th>Entire area 51.0km²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t/30d g/100m²/30d</td>
<td>t/30d g/100m²/30d</td>
<td>t/30d g/100m²/30d</td>
<td>t/30d g/100m²/30d</td>
</tr>
<tr>
<td>2009-08-24</td>
<td>3.3</td>
<td>43</td>
<td>1.8</td>
<td>28</td>
</tr>
<tr>
<td>2009-09-30</td>
<td>3</td>
<td>39</td>
<td>5</td>
<td>77</td>
</tr>
<tr>
<td>2009-11-10</td>
<td>4.3</td>
<td>56</td>
<td>7.7</td>
<td>119</td>
</tr>
<tr>
<td>2009-12-02</td>
<td>1.8</td>
<td>23</td>
<td>4.6</td>
<td>71</td>
</tr>
<tr>
<td>2010-01-12</td>
<td>4.3</td>
<td>56</td>
<td>9.4</td>
<td>144</td>
</tr>
<tr>
<td>2010-02-23</td>
<td>4.5</td>
<td>59</td>
<td>6.9</td>
<td>105</td>
</tr>
<tr>
<td>2010-03-22</td>
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<td>15.6</td>
<td>203</td>
<td>8.2</td>
<td>126</td>
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<td>2010-06-21</td>
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<td>91</td>
<td>5.3</td>
<td>81</td>
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<td>2010-07-26</td>
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<tr>
<td>2010-08-30</td>
<td>3</td>
<td>38</td>
<td>4.6</td>
<td>71</td>
</tr>
</tbody>
</table>
Dust generation from mining area depends on several factors, including the type of mining operations, characteristics of the surface material and meteorological factors. Dust from source A resulted from the filling of the open pit which also disturbed surface soil. However the filling of the pit was discontinued in March 2009, after which the dust was mainly caused by wind erosion of loose surface material around the pit. The dust mass near source A were extremely high in May 2010 (Figures 9, 10, 12) around the open pit area. They were believed to be due to a road construction at that time. The construction started in April and finished in July. To estimate the dust fallout due to the road construction the overall average dust fallout during the period without construction was calculated. The difference between the average and the monthly dust fallout during the road construction period was attributed to this activity. Since the construction took place near the open pit, the calculation used the concentrations from Area A from table 1. Table 2 shows the dusts contributed due to the road work to were 6.8, 11.8, 3.2, 0.6 t/30d. The dusts from source B were mainly attributed to the trucks traveling on haul roads and the active stockpiles (Fig. 3). The soil around the open pit contained little erodible material and belonged to the relatively low erodibility group (Jia et al., 2011).

Table 2: Net dust fallout on area A due to road construction

<table>
<thead>
<tr>
<th>Month</th>
<th>Dust due to road construction activities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t/30d</td>
</tr>
<tr>
<td>2010-04</td>
<td>6.8</td>
</tr>
<tr>
<td>2010-05</td>
<td>11.8</td>
</tr>
<tr>
<td>2010-06</td>
<td>3.2</td>
</tr>
<tr>
<td>2010-07</td>
<td>0.6</td>
</tr>
</tbody>
</table>
On the other hand, the variation of dust level in the period other than April to July seems to be closely linked to climatic variables such as rainfall, wind speed and humidity. Meteorological data were gathered from Swedish Meteorological and Hydrological Institute (Fig. 13). During September 2009 the amount of dust was very similar to that in August 2009 despite the fact that the wind velocity was higher in September. This was due to the relatively higher rainfall in that month compared to the previous month. Though the wind velocity decreased in November the dust amount increased due to the lower precipitation and the higher humidity, the later increased particle weight and enhanced particle settlement. In December the dust emission was relatively low because of the decrease in mining activities due to the Christmas holidays. The increased dusts in January and February in 2010 were mainly due to relatively low rainfall. The combined effect of low precipitation and high wind speed further increased dust emission in March in 2010. In April, May, June and July in 2010 the high dust generation level was mainly caused by the work of road construction. Finally the dust generation in August in 2010 went back to the similar level as it was in August in 2009 as the effect of road construction faded away. Those factors interact with each other, and as a consequence one factor can be counter balanced by the other factors, and this leads to the complexity of understanding the dust problem.

Fig. 13. Dust fallout, wind velocity, humidity and precipitation during August 2009 to August 2010

4. Conclusions

This paper has evaluated the dust fallout in the Malmberget area for the period of August 2001 to August 2010. Data from 26 measuring stations have been analyzed with a help of
surfer. Among all dust concentrations measured, from August 2009 to August 2010, the highest and the lowest fallout values were 1284 g/100m²/30d and 9 g/100m²/30d respectively. By contouring the mass of dust fallout two sources for dust generation were recognized. The one was the open pit, and the other one was the current mining industrial center. The variation of dust mass along a cross section passing through the two sources showed that the relative significance of two sources on dust production was shifting with time. Dust production around the Malmberget mine was attributed to three reasons, namely, wind erosion of the exposed area close to the open pit, truck transportation on haul roads, and wind erosion of and material loading and unloading at stockpiles. Since the mining activities were at a constant level, the variations of dust were mostly attributed to climate factors. It is recommended that on-site weather measurements should be introduced and observations undertaken in combination with dust measurement in order to study the relationships more accurately. Separate studies with special focus on wind erosion from an open area, haul road, and stockpiles are recommended.

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