Standardized emissions inventory methodology for open pit mining areas

Jose I. Huertas[a,*], Dumar A. Camacho[a], Maria E. Huertas[b]

[a] *Tecnológico de Monterrey, Eduardo Monroy Cárdenas No 2000. Toluca. México*

[b] *Texas A&M University, College Station, Texas 77843, USA*

Environ Sci Pollut Res
DOI 10.1007/s11356-012-0778-3
Received: 17 September 2011 / Accepted: 20 January 2012

Abstract

There is still interest in a unified methodology to quantify the mass of particulate material emitted into the atmosphere by activities inherent to open pit mining. For the case of Total Suspended Particles (TSP), the current practice is to estimate such emissions by developing inventories based on the emission factors recommended by the USEPA for this purpose. However, there are disputes over the specific emission factors that must be used for each activity and the applicability of such factors to cases quite different to the ones under which they were obtained. There is also a need for particulate matter with an aerodynamic diameter less than 10 µm (PM_{10}) emission inventories and for metrics to evaluate the emission control programs implemented by open pit mines.

To address these needs, work was carried out to establish a standardized TSP and PM_{10} emission inventory methodology for open pit mining areas. The proposed methodology was applied to 7 of the 8 mining companies operating in the northern part of Colombia, home to the one of the world's largest open pit coal mining operations (~70 Mt/year). The results obtained show that transport on unpaved roads is the mining activity that generates most of the emissions and that the total emissions may be reduced by up to 72% by spraying water on the unpaved roads. Performance metrics were defined for the emission control programs implemented by mining companies. It was found that coal open pit mines are emitting 0.726 and 0.180 kg of TSP and PM_{10}, respectively, per Mg of coal produced. It was also found that these mines are using on average 1.148 m^2 of land per Mg of coal produced per year.

Key words: emissions inventory, open-pit or open-cast mining, TSP and PM_{10}.

** Corresponding author: Tel: (33) 3 8671 5007*

E-mail address: jhuertas@itesm.mx

Present address: Eduardo Monroy Cardenas No. 2000. Toluca, Mexico. 50110.

1. Introduction

Currently the open pit coal mining activities underway in northern Colombia are regarded as the world's largest coal mining zone with more than 70 Mt/year. Colombia is the number 12 country in the list of the largest coal producer countries in the world (Energy Watch Group, 2007) and second with the largest coal reserves among the Latin-American countries (BP, 2009).

Given the economic impact of the open pit mining on the regions where it takes place, the environmental authorities promote this activity while also limiting its environmental impact. Particulate matter has important implications in cloud formation, radiation budget and multiphase processes (Zhang et al., 2008; Zheng et al., 2011). TSP and PM_{10} in open pit mining regions reduce visibility and affect surrounding flora and fauna. Additionally, they can cause black lung (CWP), silicosis and increased mortality. (Wheeler et al., 2000; NIOSH, 2005).

In some cases, even though the mining companies have adopted the control measures recommended by the environmental authorities, the problem of air polluted with particulate matter in the population centers located nearby the mining zones still persists. With time, this problem continues to worsen as the production rate of the mines increases. Open pit coal mines increased their annual production from 5 Mt in 2000 to 70 Mt in 2010.

The first step in looking at potential solutions to the air pollution problem is to quantify the mass of pollutants that is being emitted into the atmosphere.

In an open pit mine co-exist fixed (e.g. power plants), mobile (e.g. trucks, bulldozers, etc.) and fugitive (e.g., loading and unloading of material) sources of emissions. It has been found that particulate matter from no combustion sources is by far the main pollutant generated in an open pit mine (Ghose et al. 2000, 2001).

Unlike fixed and mobile sources, fugitive dust emissions from the mining operations cannot be measured. The current practice is to estimate such emissions by developing emissions inventories based on emission factors.

Axetell et al. (1978,1981), Cowherd (1982), Missouri Department of Natural Resources (2009), Muleski (1990, 1994), Shearer et al. (1981), Thompson et al. (2003), US Department of Energy (1980), USEPA (1998, 2006.a, 2006.b, 2008) and Zeller et al. (1979) have derived experimentally emissions factors for the case of individual activities involved in open pit coal mining. The validity of these emission factors is limited to the conditions under which they were obtained.

Ghose (2004, 2007) based on their own emission factors estimated that a typical open pit coal mine in India with a stripping ratio of 3.98 emitted 9366.7 kg/day of TSP while its production was 2500 t/day ie. 3.74 Kg of TSP per Mg of coal produced. The mine companies operating in Colombia have also estimated their TSP emissions following their own methodologies but they have not published them. The Australian government (2011) has established a simplified methodology to estimate pollutants inventories. However they have not made available any results yet.

The TSP emission inventories so far made differ in the emission factors used for each activity and in the activities considered which leads to large differences in the results obtained. Additionally, the emission factors used in those studies do not take into account the particular conditions of the region in terms of soil composition and the weather conditions inherent to a semi-arid tropical region. Finally, there is not any study related to PM_{10} emissions for open pit mining. Currently, environmental authorities are more interested in PM_{10} emission rather than TSP emissions given that PM_{10} are more harmful to human health than TSP. There is, consequently, a need for a standard or unified methodology to conduct the emission inventories for TSP and PM_{10}.

Work was conducted to develop a standard methodology to estimate TSP and PM10 emissions for the case of open pit mining operations along with several alternatives to assess the validity of its results. As a result, three metrics are proposed to evaluate the performance of the emissions control programs implemented in open pit mines. The methodology was applied to 7 of the 8 open pit coal mining companies operating in Colombia. A description of the methodology and the results obtained after its application are reported in the present paper.

Additionally, the precision and accuracy of those emissions inventories were evaluated following a backward air quality simulation approach (Huertas et al. 2012a). The results of the emissions inventories were incorporated into the ISC and AERMOD air quality models to assess the environmental impact of the open pit mining activities around the region where they operate (Huertas et al. 2012b). Airborne samples from the mining region were analyzed to obtain PM10 and PST concentration, particle morphology, particle size distribution and elemental composition of the particles (Huertas et al. 2012c). Finally, the particulate material dispersion and the sedimentation processes inside an open pit mine were modeled using previous results and CFD (Computational Fluid Dynamics) in order to look into new emission control alternatives. The results obtained in this last work are reported in Huertas et al. (2011).

As a result of the whole work, new emission control measures were identified. For the case of Colombia, some of these measures are being implemented under the guidance of the Colombian environmental authorities.

2. Standardized emission inventory methodology

The processes involved in open pit mining and the different extraction technologies used by several companies were studied. It was observed that open pit mining involves the following general processes:

- *Removal of the vegetable layer (top soil)*
- *Removal of overburden*
- *Removal of the useful geological material*

Each one of these mining operations is, in turn, divided into various different activities, that depend on the technologies used. Each activity is an emission source. Appendix A lists these activities.

Current methodologies to estimate the mass of TSP or PM_{10} (E_i), that is released into the atmosphere by activity *i*, are based on emission factors. The emission factor for each activity *i* ($E_{f,i}$) has been obtained by means of the following general, empirical equation (USEPA 2009).

$$E_{f,i} = \alpha \, S_a^{\beta} \, M_p^{\gamma} \, M_c^{\zeta} \qquad (1)$$

Where S_a, M_p and M_c are variables that characterize the emitting activity, material's properties and meteorological conditions, respectively. α, β, γ and ζ are experimental constants that depend on each activity and are reported in appendix A. The mass of particulate matter emitted during activity *i* (E_i) is estimated as (USEPA 2009):

$$E_i = A_i\, E_{f,i} \prod \left(1-\eta_j\right) \quad (2)$$

Where A_i is the intensity of activity i and η_j is the efficiency of the emission control measure j implemented for activity i.

For the case of open pit coal mining operations, the TSP and PM_{10} emission factors reported by the USEPA were obtained through various experimental studies carried out in mining areas in USA by the Western Institute (Axetell et al. 1978, 1981; Muleski et al. 1990, 1994; Shearer et al. 1981; US Department of Energy 1980; USEPA 2008). However these sources of information only have emission factors for some of the sub-activities involved in the open pit mining.

Here it is proposed to use these emission factors as they were originally established until local experimental studies can be made in order to adapt them to the local conditions. Furthermore, it is proposed to adopt the emissions factors reported in references USEPA (2006a, 2006b) and Missouri Department of Natural Resources (2007) for the activities not included in the previous references such as wind erosion, handling and storage in piles and transportation over unpaved roads. Appendix A lists and classifies all these emission factors.

2.1 Special considerations

Emission factors for loading and unloading of materials. For the case of loading and unloading of soil, overburden and the useful geological material, it was used the emission factor ($E_{f,l}$) reported by the USEPA (2006b) for aggregate handling and storage in piles of granulated material

$$E_{f,l} = \alpha \frac{\left(U/2.2\right)^{1.3}}{\left(M/2.0\right)^{1.4}} \quad (3)$$

Where U is the mean wind speed, M is the material´s moisture content and α is a constant equal to 0.0012 for TSP and 0.00056 for PM_{10}. Equation 3 is valid for materials with silt content between 0.44% and 19%, material's moisture content between 0.25% and 4.8% and wind speed conditions between 0.6 m/s and 6.7 m/s. However most of the applications in open pit mining are outside these rages. Figure 1 shows for the case of TSP the behavior of equation 3 in these ranges of validity.

Given the difficulty of obtaining this emission factor for ranges outside of those specified above, it is proposed to use this emission factor under the conditions representing the worst case scenario. That is, the value of 4.8 will be used in equation 3 for applications where the material moisture content exceeds 4.8%. If the wind speed is greater than 6.7 m/s, the actual wind speed value will be used in equation 3.

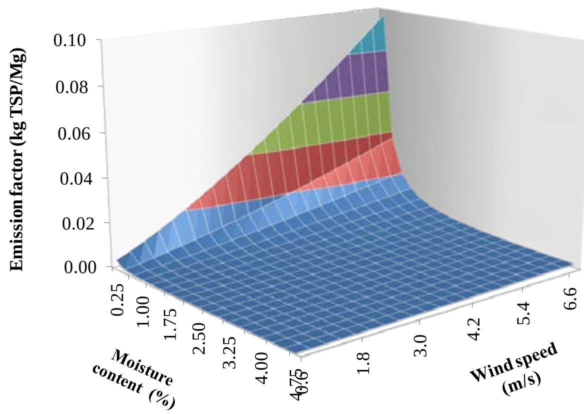

Fig. 1. *TSP emission factor for loading and unloading processes as function of material's moisture content and wind speed.*

Emission control measures. Various emission control techniques have been developed for the transportation of cargo on unpaved roads. All of them are based on spraying water on the roads, with or without additives. Cowherd et al. (1988) estimated the efficiency of emission control by spraying water (η_s) without additives by means of the following equation:

$$\eta_s = 1 - \left(\frac{0.8\, p\, r\, t}{k} \right) \qquad (4)$$

Where p is the average daytime evaporation rate, r is the average daily traffic, k is the intensity of the applications in l/m^2 and t is the average time between spray applications.

Additionally, USEPA (2006a) estimated the efficiency of particulate matter emission control (η_r) through natural spraying (rain) by means of the following equation:

$$\eta_r = 1 - \left(\frac{m - n}{m} \right) \qquad (5)$$

Where m is the number of days in the period and n is the number of rainy days in the period with precipitation levels exceeding 0.254 mm.

Since water availability is always an issue during dry seasons, mine companies are continuously looking for new technologies to increase emission control efficiencies minimizing water usage and cost. Available technologies are based on water additives that reduce water evaporation and maintain particular matter agglomerated over the unpaved roads. Table 1 lists and compares these types of technologies. Additional work is required to quantify the actual efficiencies of these technologies by on site tests.

Table 1.
Technologies to control particle emission from unpaved roads.

	Working mechanisms	***Advantages***	***Disadvantages***	***Products***
Water	Wets the particles increasing their mass and agglomerating them	• Low cost, easy to apply • Minimum environmental impact	• It requires regular applications • Overwatering cause deterioration of roads and operational problems	N/A
Salts	Hydroscopic substance. Attract and retain soil moisture	• Reduce evaporation to 1/3 • It compacts the material of the road • It does not disappear with the maintenance of the road	• It is corrosive • Disappear with rain • Have environmental impact (ions)	Roadmag
Surfactants	Reduce surface tension of water	• Ease to apply and flexible	• Low residual effects	Drimax 1235 Perma -Zyme RT9 Durasoil
Resin emulsions	Act as adhesive substances Agglomerates the fine particles of the road	• Low solubility • Non corrosive • Seals the surface against water	• Disappear with the maintenance of the road • Limited to heavy use	Pavcryl Alcotac DS1 Soiltac
Lignin derivates	Act as adhesive substances Agglomerates the fine particles of the road	• No water requirement • It does not disappear with the maintenance of the road	• Disappear with the rain • Slippery when it is wet • Have environmental impact (ODB)	Perma-Zyme Alcotac DS7 Durasoil
Bitumens	Agglomerates the fine particles of the road Pave the road	• Insoluble in water • Seals the surface against water • Appropriate for long-term applications	• Highly costly • Have environmental impact (HCs)	Dust-a-side Jegel Dust stop SLS Used oil
Polymers	Act as adhesive substances Agglomerates the fine particles of the road	• More effective agglomeration than resins • Appropriate for long-term applications • Low environmental impact	• Require regular applications	RT9

2.2 Implementation of the methodology on a spreadsheet

In order to standardize and facilitate the development of TSP and PM_{10} emission inventories, equations 1 to 5 were implemented on a spreadsheet for all of the activities involved in the open pit mining operation. For the sake of convenience, the results obtained were grouped into the following operations: soil handling operations, drilling and blasting, handling overburden, handling coal, wind erosion and transportation. Appendix A lists the operations and activities considered.

Since emission inventories expressed by areas are required as input data for air quality models, the results obtained were regrouped by the location of the sources in the following physical areas: Pit, Dumps, Coal storage piles and Roads. The routes considered were: from the pit to the dump, from the pit to the storage piles and from the storage piles to the mine limits. Appendix A shows how this regrouping was made.

It was found that the volume of information required to complete the emissions inventory is high and, in some cases, mining companies do not have all this information available. In the cases of non-critical information, algorithms that make possible to estimate this missing information were incorporated by using historical records and experimental readings obtained from alternate sources, such as average meteorological conditions, soil characterization, etc.

Additionally, algorithms to alert the user about potential errors in the emission inventory input data were incorporated into this spreadsheet. This was done through statistical identification of non typical values. That is, data that is outside of the confidence interval with a level of certainty of 95% (Devore 2001). Finally, shielding tools were incorporated into the spreadsheet that allows the environmental authority to ensure that the emission inventories made by the mining companies follow the same procedures and the same calculation methodology. It also incorporated the feedback of several coal mining companies, environmental authorities and private consulting firms in a process that lasted almost 2 years. Finally, a manual was written to assist the users in the emission inventory preparation process.

3. Results

As an example of its applicability, the standardized emissions inventory methodology for open pit mining was applied to 7 of the 8 open pit coal mine companies operating in the north part of Colombia for the years 2007, 2008 and 2009. The coal mines operational parameters were provided directly by each company. The following analyses were made in order to assess the validity of the emission inventories obtained through the standardized methodology.

3.1 Comparison of the operational parameters reported by coal mining companies

Statistical analysis of the data reported by the mine companies was performed to identify non typical values. These values were double checked with the respective companies. Table 2 reports the average values of the mines operational parameters reported by the companies.

3.2 Comparison by total emissions

Figures 2.a and 2.b show the kg of TSP and PM_{10} (respectively) emitted per Mg of annual coal production. It was obtained a high value for the coefficient of determination ($R^2=0.909$ for TSP and $R^2=0.849$ for PM_{10}) in the linear correlation analysis between these two variables indicating that there is a high linear correlation between particulate matter emissions and mining production. It was also found that on average a mine company generates 0.726 kg of PST and 0.180 kg of PM_{10} (respectively) per Mg of coal produced. For the case of India, Ghose (1989, 2007) reported a value for this metric of 3.74 kg/Mg for an open pit coal mine with a stripping ratio of 3.98. This reference does not mention the use of any emission control measure. Here, it is proposed the ratios of TSP and PM_{10} to the annual production as the first metrics to evaluate the performance of the emission control programs implemented by the open pit mining companies.

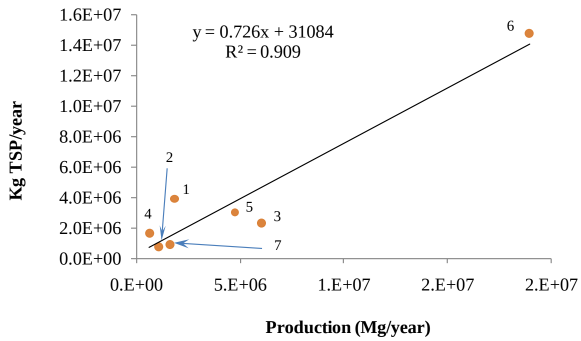

Fig. 2.a. *kg of* ***TSP*** *emitted per Mg of coal produced by 7 open pit coal mines in Colombia during 2009 as function of their annual production*

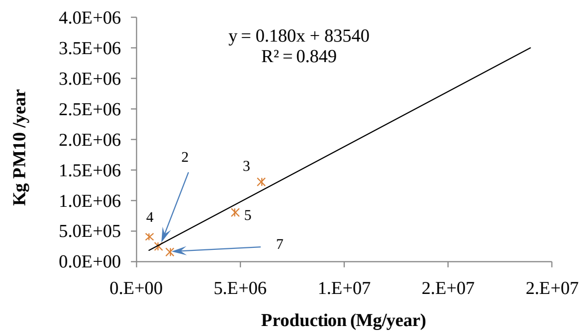

Fig. 2.b. *Kg of* $\boldsymbol{PM_{10}}$ *emitted per Mg of coal produced by 7 open pit mines in Colombia during 2009 as function of their annual production.*

Table 2
Main operational parameters of open pit coal mining.

Description			Units	Average	Min	Max	Std desv	n
Physical properties	Density	Topsoil	Mg/m^3	1.83	1.20	2.40	0.35	20
		Overburden	Mg/m^3	2.41	2.10	3.00	0.17	20
		Coal	Mg/m^3	1.30	1.25	1.30	0.01	16
	Silt content	Topsoil	%	10.7	2.0	30.0	11.6	16
		Overburden	%	5.5	2.0	20.0	4.2	16
		Coal	%	4.3	1.7	10.0	1.8	16
	Moisture content	Topsoil	%	12.5	6.0	15.0	3.5	16
		Overburden	%	8.8	2.9	12.0	2.6	16
		Coal	%	10.2	6.0	13.0	2.8	16
Operational parameters	Overburden to carbon ratio		Mg/Mg	15.1	5.5	35.2	9.20	16
	Topsoil to carbon ratio		Mg/Mg	0.26	0.00	3.41	0.84	16
Land use	Overburden	Pit and dump	Ha	297.7	2.5	1569.3	369.4	16
	Coal	Stock	Ha	11.7	2.0	36.2	9.0	16
Meteorology	Days with precipitation > 0.254 mm		days/period	102.2	2.0	152.0	44.4	16
	Evaporation rate		mm/h	1.30	0.04	4.50	1.61	16
	Average wind speed		m/s	1.58	1.19	1.89	0.24	16
	% of wind speed >5.33 m/s		%	4.2	0.0	50.0	12.2	16

Figure 3 shows the total area used by each coal company in the mining process as function of its annual production. As in the previous case, this figure shows that there is a high linear correlation between these two variables ($R^2=0.945$) and that on average mining companies use 1.148 m^2 for every Mg of coal produced per year. This ratio assesses land use. It evaluates the extension of the areas exposed to wind erosion, length of unpaved roads used for transportation, size of the pit area and the extension of land used for coal handling and storage. This parameter corresponds to the second metric to evaluate the performance of the emission control programs implemented by the open pit mining companies.

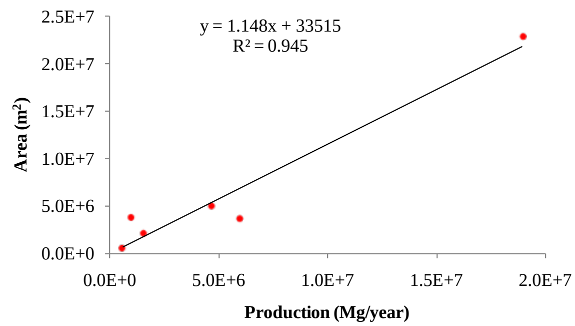

Fig 3. *Total area used by companies in the open pit mining process as function of its annual production*

3.3 Comparison of emissions by mining activities

Figures 4.a and 4.b show the contribution of each general activity to the emissions of TSP and PM_{10} respectively. Cowherd (1988) estimated that 50% of the total TSP is emitted during the transportation of material over unpaved roads within the mine. Here it was found that by spraying water over these unpaved roads, companies have been able to reduce TSP emissions by 72%, on average. Companies reported that they spray water between 1 and 2 l/m^2 between 2 to 4 times every hour and that they obtain 99% of efficiency in controlling particulate matter emission according to equation 4. Further work is required to validate the applicability of equation 4 to the local conditions and to establish the appropriate spraying parameters to minimize water use.

Figure 4.a shows that on average, transportation over unpaved roads still represent the largest emission source with a 34% of contribution to the total emissions of TSP. It is followed by coal handling and wind erosion with a contribution of 29% and 28% respectively. This result agrees with Chaulya (2004, 2005) who reported that material handling and wind erosion are the other two main source of TSP.

For the case of PM_{10}, the contributions to the total emissions are quite different. On average 52% of the PM_{10} emissions are due to overburden handling, 25% to transportation and 16% to coal handling as it is shown in figure 4.b.

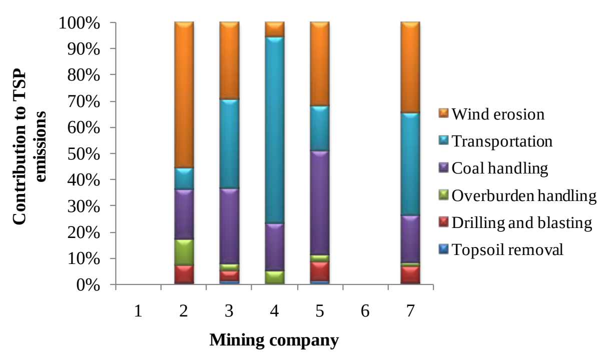

Fig 4.a. Contribution to ***TSP*** *emissions of the activities involved in open pit mining for the case of coal production in Colombia during 2009.*

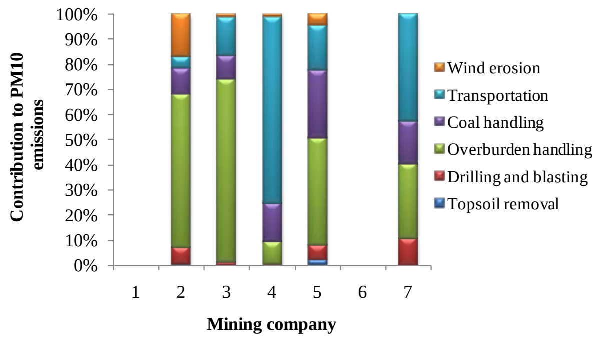

Fig. 4.b. Contribution to ***PM*$_{10}$** *emissions of the activities involved in open pit mining for the case of coal production in Colombia during 2009.*

3.4 Comparison of emissions by area source

As it was mentioned previously, emissions were rearranged by the location of the sources as indicated in appendix A. Results for the 7 companies were averaged. Figures 5.a and 5.b show the average of the contribution of each area being considered to the total emission of TSP and PM_{10} respectively. Figure 5.a shows that pits and dumps are the main areas sources of emissions with an average contribution of 42% and 18% to the total emissions of TSP, respectively.

Similarly, figure 5.b shows that the dumps and the pits are the main area sources of PM_{10} emissions with a contribution of 60% and 16% respectively.

Emissions from dumps are of greater concern since they are located at the highest point of the mine and therefore have the potential of being transported by wind action for the longest distance outside of the mine. Even though emissions from pits are important in quantity, a high percentage of them remain within the pit due to air recirculation within the mine (Silvester et al. 2009; Huertas el al 2011).

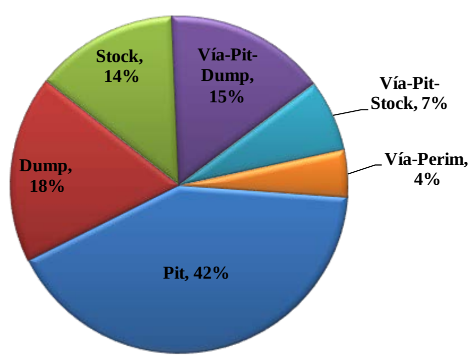

Fig 5.a. *Average contribution to* ***TSP*** *emissions of each area source present in open pit mining for the case of coal production in Colombia during 2009.*

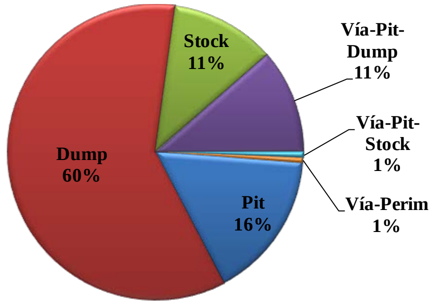

Fig 5.b. *Average contribution to* $\boldsymbol{PM_{10}}$ *emissions of each area source present in open pit mining for the case of coal production in Colombia during 2009.*

4. Recommendations

It is recommended to the environmental authorities to establish the following metrics to evaluate the performance of the emission control programs implemented by open pit mining companies.

- *Emission index:* Defined as the total mass of particulate matter emitted to the atmosphere, estimated through an emission inventory, divided by the company's annual production. This index can be reduced, for example, by watering areas exposed to wind erosion, avoiding material transportation on unpaved roads (use of trains and conveyors), generating barriers to wind circulation around piles and coal grinders, increasing moisture content of coal and overburden etc. For the case of coal mining in Colombia this metric has a value of 0.726 and 0.180 kg/Mg for TSP and PM_{10}, respectively.
- *Land use index:* Defined as the total area exposed to wind action, length of unpaved routes, pit areas, and dump areas etc divided by the company's annual production. Mine companies can reduce this metric by minimizing route lengths and by reducing uncovered areas used as dumps and pits through reforestation. For the case of coal mining in Colombia this metric has a value of 1.148 (m^2/Mg)/year.
- *Emission control efficiency by water spraying:* This metric corresponds to the efficiency obtained by equation 4 for a given water spraying program (Intensity of the applications and average time between spray applications) over unpaved roads and areas exposed to wind erosion. For the case of coal mining in Colombia this metric has a value of 99%.

5. Conclusions

It was presented a standardized methodology to carry on TSP and PM_{10} emissions inventories for open pit mining. It is based mainly on the USEPA emission factors. It was implemented in a spreadsheet and made available to the public domain through internet. Several tools were implemented within the spreadsheet to prevent typographical errors and to facilitate its use. It also has incorporated the feedback of coal mining companies, environmental authorities and private consulting firms.

The emission inventories can also be used to identify the sub-activities within the mining operation that require additional effort to control particle emissions.

This tool was used to obtain the TSP and PM_{10} emission inventories of 7 out of 8 open pit coal mining operating in the northern part of Colombia, which is considered as one of the largest open pit coal mining areas of the world. Results showed that on average these companies emit 0.726 kg of TSP and 0.180 kg of PM_{10} per Mg of coal produced, that on average they use 1.148 m^2 per Mg of coal produced yearly and that they control particle emission from unpaved roads with a 99% of efficiency by water spraying. Companies reported that by spraying water between 1 and 2 l/m^2 between 2 to 4 times every hour, they have been able to reduce on average 72% of TSP emissions. However transportation of material over unpaved roads is still the main source of TSP followed by coal handling and wind erosion.

Additional work is required to adapt the emission factors implemented in the proposed methodology to the local particular conditions of each mine. Further work is also required to determine the conditions of water spraying (Intensity of the applications and average time between spray applications) that minimize water use and cost of the particle emission control programs for open pit mines.

Appendix A

Table A.1

Activities involved in open pit mining and its classification by area source.

Operation	***Activity***	***Equation ID***		***Classification by area source***
		PST	***PM_{10}***	
Topsoil handling	Top soil removal by scraper	1	0	Pit
	Bulldozing	2	20	Pit
	Loading	3	21	Pit
	Transportation	4	22	Pit 25%, dump 25%, roads 50%
	Unloading	5	21	Dump
Drilling and blasting (Coal and overburden	Drilling	6	0	Pit
		7	0	Pit
	Blasting	8	23	Pit
		8	23	Pit
Overburden handling (traditional way)	Bulldozing in the loading area	9	24	Pit
	Loading	3	21	Pit
	Transportation by trucks	4	22	Pit 25%, dump 25%, roads 50%
	Unloading	10	21	Dump
	Bulldozing in the unloading area	9	24	Dump
Overburden handling by dragline and conveyor	Overburden removal with dragline	11	25	Pit
	Truck loading with dragline	11	25	Pit
	Bulldozing in pits	9	24	Pit
	Truck loading with bulldozer y/o feeder	3	21	Pit
	Transportation by truck	4	22	Pit 25%, dump 25%, roads 50%
	Truck unloading	10	21	Dump
	Chute loading with scrapper	3	21	Pit
	Overburden unloading from conveyor	10	21	Dump
	Bulldozing in the unloading area	9	24	Dump
Coal handling	Bulldozing	2	20	Pit
	Truck loading	12	26	Pit
	Transportation by truck	4	22	Pit 25%, dump 25%, roads 50%
	Unloading	13	21	Patio
	Stocking with bulldozer	2	20	Patio
	Train loading	14	21	Patio
	Transportation by train	15	0	Roads

Operation	*Activity*	*Equation ID*		*Classification by area source*
		PST	PM_{10}	
Other operations	Wind erosion in coal piles	16	27	Patio
	Wind erosion in exposed areas	17	27	Dump
	Road maintenance	18	28	Pit
	Light duty traffic	19	29	Pit 25%, dump 25%, roads 50%

Table A.2
TSP and PM_{10} emission factors used for each activity involved in open pit mining.

Equation ID	*Equation*	*Units*	*Reference*
1	0.029	kg PST/t	(US EPA, 2008)
2	$35.6\frac{s^{1.2}}{M^{1.4}}$	kg PST/h	(US EPA, 2008)
3	$0.0012\frac{\left(U/2.2\right)^{1.3}}{\left(M/2\right)^{1.4}},\quad 0.018*$	kg PST/t	(US EPA, 2006b)
4	$1.38\left(\frac{s}{12}\right)^{0.7}\left(\frac{W}{3}\right)^{0.45}(1-\eta_s)(1-\eta_r)$	kg PST/VKT	(US EPA, 2006a; Cowherd, 1988)
5	$0.0012\frac{\left(U/2.2\right)^{1.3}}{\left(M/2\right)^{1.4}},\quad 0.02*$	kg PST/t	(US EPA, 2006b, 2008.)
6	0.59	kg PST/hole	(US EPA, 2008)
7	0.1	kg PST/hole	(US EPA, 2008)
8	$0.00022\,A^{1.5}$	kg PST/blast	(US EPA, 2008)
9	$2.6\frac{s^{1.2}}{M^{1.3}}$	kg PST/h	(US EPA, 2008)
10	$0.0012\frac{\left(U/2.2\right)^{1.3}}{\left(M/2\right)^{1.4}},\quad 0.001*$	kg PST/t	(US EPA, 2006b, 2008)
11	$0.0046\frac{d^{1.1}}{M^{0.3}}$	kg PST/m^3	(US EPA, 2008)
12	$\frac{0.58}{M^{1.2}}$	kg PST/t	(US EPA, 2008)
13	$0.0012\frac{\left(U/2.2\right)^{1.3}}{\left(M/2\right)^{1.4}},\quad 0.033*$	kg PST/t	(US EPA, 2008)
14	$0.0012\frac{\left(U/2.2\right)^{1.3}}{\left(M/2\right)^{1.4}},\quad 0.014*$	kg PST/t	(US EPA, 2008)
15	$1.8U^*$	Kg PST/(Ha h)	(US EPA, 2008)
16	$1.8U$	Kg PST/(Ha h)	(US EPA, 2008)
17	0.85	Ton PST/(Ha-year)	(US EPA, 2008)
18	$0.0034\,S^{2.5}$	kg PST/VKT	(US EPA, 2008)
19	$\frac{1.6914\left(s/12\right)\left(S/30\right)^{0.3}}{\left(M/0.5\right)^{0.3}}-1.325E-4$	kg PST/VKT	(US EPA, 2006a)
20	$0.75(8.44)\frac{s^{1.5}}{M^{1.4}}$	kg PM_{10}/(h bulldozer)	(US EPA, 2008)
21	$0.00056\frac{\left(U/2.2\right)^{1.3}}{\left(M/2\right)^{1.4}}$	kg PM_{10}/t	(US EPA, 2006.)

Equation ID	Equation	Units	Reference
22	$0.423\left(\frac{s}{12}\right)^{0.9}\left(\frac{W}{3}\right)^{0.45}(1-\eta_s)(1-\eta_r)$	kg PM_{10}/VKT	(US EPA, 2006a.; Cowherd, 1988)
23	$0.52\,(0.00022)A^{1.5}$	kg PM_{10}/blast	(US EPA, 2008)
24	$0.75\,(0.45)\,\frac{s^{1.5}}{M^{1.4}}$	kg PM_{10}/h	(US EPA, 2008)
25	$0.75\,(0.0029)\frac{d^{0.7}}{M^{0.3}}$	kg PM_{10}/m^3	(US EPA, 2008)
26	$0.75\,\frac{0.0596}{M^{0.9}}$	kg PM_{10}/t	(US EPA, 2008; Missouri Department of Natural Resources, 2007)
27	$9.5E-5\,\frac{s}{1.5}\,b\left(\frac{c}{235}\right)\frac{e}{15}$	Kg $PM_{10}/(m^2$ year)	(Missouri Department of Natural Resources, 2007)
28	$0.60\,(0.0056)\,S^{2.0}$	kg PM_{10}/VKT	(US EPA, 2008; Missouri Department of Natural Resources, 2007)
29	$0.507\,\frac{\left(s/12\right)\left(S/30\right)^{0.2}}{\left(M/0.5\right)^{0.5}}(1-\eta_s)(1-\eta_r)$	kg PM_{10}/VKT	(US EPA, 2006a; Cowherd, 1988)

List of symbols

A	*Blasting horizontal area with a dept <21 m. (m^2).*
A_i	*Intensity of activity i.*
b	*Days of stocking or exposition (days).*
c	*Dry days during the year(days).*
d	*Average high where the material is released (m).*
e	*% of wind speed >5.33 m/s (%).*
E_i	*Estimate the mass of TSP or PM_{10} that is released into the atmosphere by activity i (kg/year).*
$E_{f,l}$	*Emission factor for aggregate handling and storage in piles of granulated material (kg PST/t) .*
$E_{f,i}$	*Emission factor for activity i (kg/intensity of activity i).*
k	*Intensity of the applications (l/m^2).*
m	*Number of days in the period (days).*
M:	*Moisture content of the handled material (%).*
M_p	*Material's properties.*
M_c	*Meteorological conditions.*
p	*Average daytime evaporation rate (mm/h).*
n	*Number of rainy days in the period with precipitation levels exceeding 0.254 mm (days).*
r	*Average daily traffic (vehicles/h).*
R^2	*Coefficient of determination.*
S_a	*Emitting activity.*
S	*Average vehicle speed (km/h).*
s	*Silt content (mesh 200) of the handled material or on the surface of the road (%).*
t	*Average time between spray applications (h).*
U	*Wind speed (m/s).*
*U**	*Average train speed (m/s).*
VKT	*Kilometers traveled per vehicle (km/vehicle).*
W:	*Truck average weight (t).*
i,j	*Indexes.*
$\alpha,\beta,\gamma,\zeta$	*Experimental constants.*
η_j	*Efficiency of the emission control measure j (%).*
η_s	*Efficiency of emission controls for spraying water (%).*
η_r	*Efficiency of particulate matter emission control through natural spraying (rain) (%).*
*	*Constant values area applied whenever equations are not applicable.*

6. Acknowledgments

This work was financed by the Colombian Ministry of the Environment.

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