Environmental Modelling & Software 17 (2002) 467–480

Environmental Modelling & Software

www.elsevier.com/locate/envsoft

Determination of the emission rate from various opencast mining operations

M.K. Chakraborty *, M. Ahmad, R.S. Singh, D. Pal, C. Bandopadhyay, S.K. Chaulya

Central Mining Research Institute, Barwa Road, Dhanbad 826 001, India

Received 8 August 2000; received in revised form 9 November 2001; accepted 24 November 2001

Abstract

A study was carried out to determine the emission rate and develop an empirical formulae to calculate the emission rate of various opencast mining activities. The results of the study can be utilized by the mine environmental engineers and scientists working in the field of air quality monitoring for the advance prediction of a likely impact due to any upcoming project.

To achieve the objectives, seven coal and three iron ore mining sites have been selected to generate emission data for major mining activities by considering type of mining, method of working, geographical location, accessibility and above all resource availability.

Based on the study a set of 12 empirical formulae has been developed for the calculation of the suspended particulate matter emission rate from various opencast coal/mineral mining activities. The emission of gaseous pollutants (sulphur dioxide and nitrogen oxide) has been found to be negligible for various mining activities. Therefore, observation for gaseous pollutants has been considered for overall mining activities and subsequently empirical formulae have been developed.

Validation of the developed empirical formulae has been carried out by conducting a field study at the Rajpura mine. The measured and calculated values of the emission rate have been compared for each activity. The average accuracy between the measured and calculated values for different activities has been found to vary between 77.2 and 80.4%.

Keywords: Opencast coal mine; Air pollution; Emission rate; Dispersion modelling; Software

1. Introduction

In India, mining being the foremost core sector industry plays an important role in the changing economic facet of the country and is essential for keeping pace with industrialization and attaining higher standards of living. Right from exploration to the processing of end product i.e. mineral processing, all major mining activities directly or indirectly contribute in the emission of pollutants leading to the problem of air pollution and related health hazards. The growing emphasis on opencast mining operations in recent years to achieve ever increasing production targets has further aggravated the problem of air pollution. Therefore, a detailed study on emission sources (for determination of emission rate of various mining activities) and quantification of pollutant concentrations (by means of dispersion modelling) is required to assess the environmental impact of a proposed opencast site (Jones, 1993; Rao, 1996; CMRI, 1998). Determination of the emission rate for various mining activities which are unique in nature, will help practicing mine environmental engineers and mine managers to get prior information on the likely impact on air quality. On the basis of the predicted increments to air pollutant concentrations, effective mitigative measures including the design of a green belt can be devised for sensitive areas (Kapoor and Gupta, 1984; NEERI, 1993; Shannigrahi and Agarwal, 1996).

Cowherd (1982) and USEPA (1995) have derived empirical formulae for the determination of emission rates for western surface coal mining activities. However, the rate of emissions from Indian mines are different from those of USA due to the distinctively different geo-mining conditions, site practices and prevalent micro-meteorological conditions (CMRI, 1998). Hence,

* Corresponding author. Tel.: +91-326-203010/203070/203090; fax: +91-326-202429/202083/202774/202093.

E-mail addresses: rss_60@yahoo.com (R.S. Singh); debjit_pal@yahoo.com (D. Pal); cbandopadhyay@yahoo.com (C. Bandopadhyay).

1364-8152/02/$ - see front matter
PII: S1364-8152(02)00010-5

the same empirical formulae for the determination of emission rates can not be considered for Indian mines. In India, only limited studies on the characterization of dust in opencast mines have been conducted by various researchers, namely, Kumar et al. (1994); Sinha and Banerjee (1994); Sinha (1995); Sinha and Banerjee (1997) and Soni and Agarwal (1997). Therefore, a detailed study has been taken up for the determination of the emission rate from different opencast mining operations and the development of empirical formulae for each activity along with a user-friendly software.

2. Methodology

2.1. Approach

The procedure followed during field monitoring, laboratory analysis and modelling exercise are outlined in the form of a flow chart (Fig. 1) to achieve the objectives of the study.

2.1.1. Site selection

Study sites have been selected on the basis of type of mining, method of working, location and accessibility with an eye on logistics. A total of seven opencast coal mines and three iron ore mines have been selected for the generation of data for the development of empirical formulae for the determination of emission rate of each mining activity and another opencast coal mine has been selected for validation study.

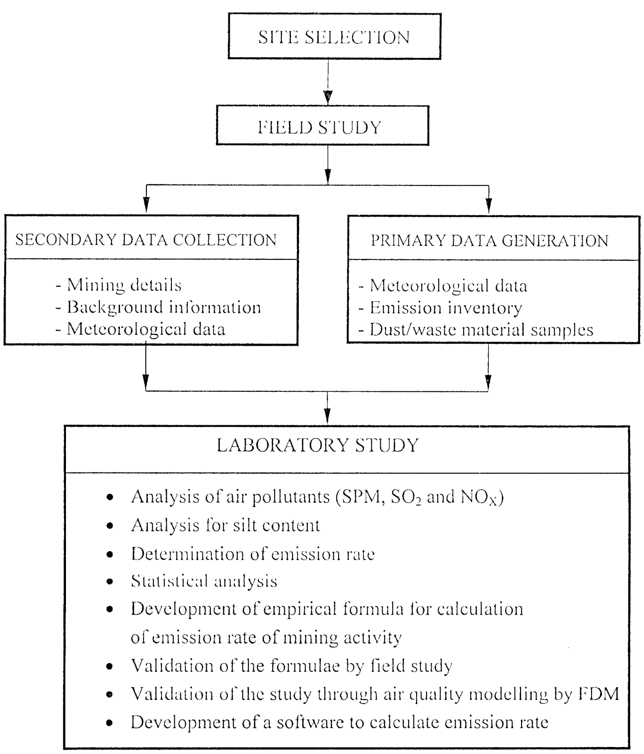

Fig. 1. Approach for the study.

2.1.2. Study sites

Different study sites have been selected as discussed earlier, to generate site specific emission data for various opencast mining activities. Sasti, Lakhanpur, Belpahar, Ananta, Jagannath, Block II and Kusunda coal mines and Noamundi, Bicholim and Kirlepale iron ore mines have been selected for the development of empirical formulae for the determination of the emission rate of each mining activity and Rajpura mine has been demarcated for validation study. A brief description of the location of all the 11 sites are given in Table 1 while a summary of topography, climate and mining details are enumerated in Table 2. The location of study sites is given in Fig. 2.

2.1.3. Secondary data collection

The secondary data regarding mining details, geology, meteorological data, etc. have been collected from various sources, like a mine plan, an environmental management plan and management of the respective mine.

2.1.4. Primary data generation

Primary data generated can broadly be categorized under three major sub-headings, namely, micro-meteorological data, emission inventory data and finally dust or waste material quality data (for parameters like silt content, moisture content, etc.). The study has been conducted during the winter season (1997–98) to evaluate the worst possible scenario of air pollution due to a low ventilation coefficient.

2.2. Micro-meteorological parameters

Hourly micro-meteorological data has been generated by installing an automatic weather monitoring station (Omnidata International Inc., USA) at the respective study sites during the study period (winter season) for monitoring different parameters such as wind speed and direction, ambient air temperature, relative humidity, total rainfall and atmospheric pressure. Emission data has been generated for each type of mining activity i.e. drilling, overburden loading and unloading, coal/mineral loading and unloading, haul and transport road, stock yard, exposed overburden dumps, coal handling/ore processing plant, exposed pit face and workshop as per the USEPA methodology. Long term meteorological data have also been collected from the nearest meteorological station from the Indian Meteorological Department for the respective areas. A doppler SODAR (sound detection and ranging) has been installed at Rajpura mine to generate detailed micro-meteorological data, including mixing height for air quality modelling (validation study). A windrose diagram has been prepared from the data with stability class including calm periods (defined as a wind

Table 1
Brief description of the study sites[a]

Sl	Name of the mine	Location				Mining Area	Company
		District	State	Latitude (N)	Longitude (E)		
1	Sasti	Chandrapur	Maharastra	18°48’05”	79°18’25”	Wardha Valley	WCL
2	Lakhanpur	Jharsuguda	Orissa	21°45’15”	83°50’38”	Ib Valley	MCL
3	Belpahar	Jharsuguda	Orissa	21°46’10”	83°51’52”	Ib Valley	MCL
4	Ananta	Angul	Orissa	20°59’13”	85°09’05”	Talcher	MCL
5	Jagannath	Dhenkanal	Orissa	20°56’20”	85°08’10”	Talcher	MCL
6	Block II	Dhanbad	Bihar	23°46’05”	86°12’31”	Jharia	BCCL
7	Kusunda	Dhanbad	Bihar	23°47’25”	86°14’15”	Jharia	BCCL
8	Noamundi	W. Singhbhum	Bihar	22°9’	85°29’	Noamundi	TISCO
9	Bicholim	N. Goa	Goa	15°35’36”	73°54’43”	Goa	DEMPO
10	Kirlepale	N. Goa	Goa	15°16’50”	74°09’24”	Goa	DEMPO
11	Rajpura	Burdwan	West Bengal	23°46’55”	86°43’45”	Raniganj	ECL

[a] WCL, Western Coalfields Ltd; MCL, Mahanadi Coalfields Ltd; BCCL, Bharat Coking Coal Ltd; ECL, Eastern Coalfields Ltd.

Table 2
Background information of the study sites

Sl	Name of the mine	Surface reduced level (m)	Climate		Mining details		
			Annual rainfall (mm)	% of calm	Leasehold area (ha)	Annual production (Mt)	Striping ratio (m^3/t)
1	Sasti	270–282	1250	34.8	653.9	1.0	3.70
2	Lakhanpur	198–250	1400	38.4	1260.0	1.0	1.01
3	Belpahar	199–251	1400	38.4	1601.0	2.0	2.31
4	Ananta	95–125	1200	40.0	572.0	4.0	0.51
5	Jagannath	102–127	1150	38.3	793.2	4.0	0.60
6	Block II	176–240	1375	39.1	755.5	2.5	4.49
7	Kusunda	160–226	1400	38.4	235.30	1.5	3.20
8	Noamundi	–	1400	38.0	1740.00	4.26	10.00[a]
9	Bicholim	156.98–15	2500	3.13	479.30	1.7	2.30
10	Kirlepale	156.98–15	2560	3.13	82.50	0.5	2.80
11	Rajpura	93–127	1450	32.7	174.0	1.0	2.30

[a] OB is thin but stripping ration mentioned includes rejects.

speed <0.4 m/s). Atmospheric stability classes (Pasquill–Gifford) have been computed using the Turner classification scheme (Viswanathan et al., 1995; Herrmann and Hanel, 1997).

2.3. Air quality parameters

Air quality has been monitored through high volume samplers with an average flow rate of >1.1 m^3/min. The parameters considered for field monitoring have been suspended particulate matter (SPM), sulphur dioxide (SO_2), and various nitrogen oxides (NO_x). Mean samples of SPM, SO_2 and NO_x have been collected for 24 h following the national ambient air quality standard (NAAQS) protocol. Standard methods have been used for analysis of the data as given in Table 3 (Stern, 1968). Monitoring at each point has been triplicated and an average of three readings has been considered for the study. During the field study it has been found that SPM is the major source of emission from various opencast mining activities; whereas emission of SO_2 and NO_x from most of the activities has been negligible as in most parts of the mine electrically operated machine is used except in transportation. In the study sites no coal combustion has been found to take place. Therefore, gaseous emissions have been measured considering the mine as a whole.

2.4. Emission inventory

An emission inventory study has been carried out to evaluate the amount of different pollutants contributed by each mining activity. Blasting has not been considered as it is an instantaneous source. The concen-

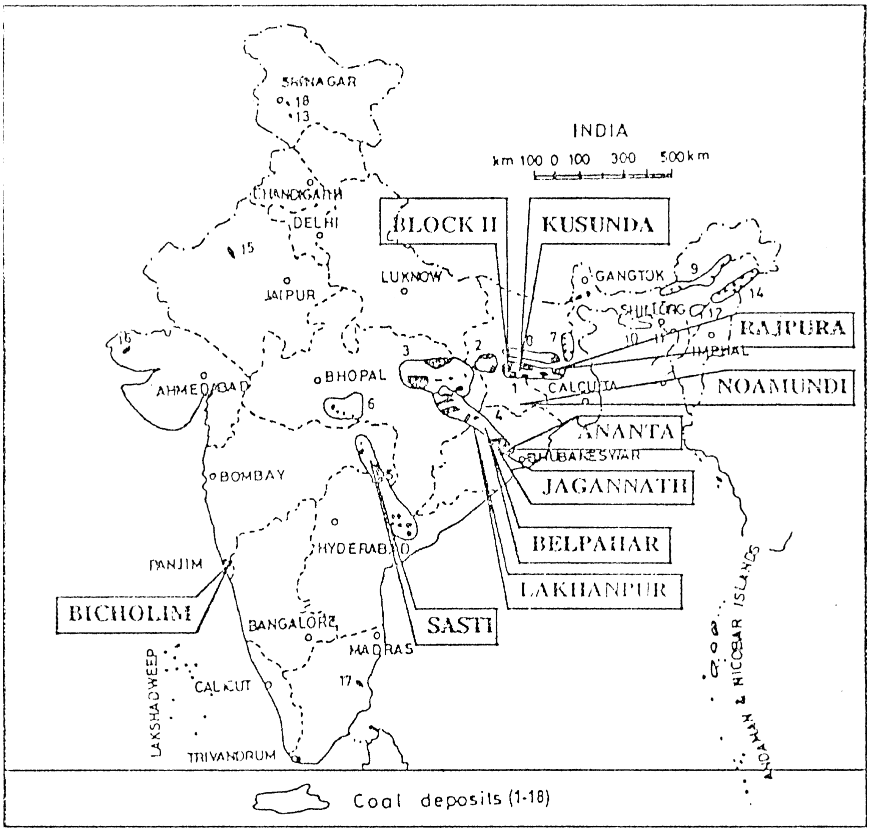

Fig. 2. Location of the study site.

Table 3
Air pollutant analysis methods

Parameter	Method	Instruments
SPM	Measurement of weight (IS: 5182 Part XIV)	High volume sampler (HVS) with an average flow rate >1.1 m^3/min (Model APM 415 Envirotech Instruments Pvt. Ltd)
SO_2	Improved West and Gaeke Method (IS: 5182 Part II)	HVS with gaseous sampling arrangement (Model APM 415 Envirotech Instruments Pvt. Ltd) and spectrophotometer (Milton Roy, Spectronic 20 D)
NO_x	Jacob and Hochheiser modified method (IS: 5182 Part II)	HVS with gaseous sampling arrangement (Model APM 415 Envirotech Instruments Pvt. Ltd) and spectrophotometer (Milton Roy, Spectronic 20 D)
Wind speed and direction, Rainfall, R.H., etc	Sensor based	Automatic Digital Weather Monitoring Station, OMNIDATA International, USA
Mixing height	Analysis of modulated sound wave	Doppler Acoustic SODAR, REMTECH France
Particle size (silt content)	IS 2720 Part V (1985)	Shieve (mess 4 mm, 2 mm, 125 μm and 75 μm)
Moisture content	Measurement of Weight, IS 2720 Part II (1973)	Oven and electronic balance (Mettler)

tration of air pollutants with respect to different mining activities has been determined at both upwind and downwind (two locations) directions. Difference in concentrations between the downwind (maximum of the two readings) and upwind directions has been used to determine the emission rate for the respective mining operation. The emission rates of different mining activities have been calculated on the basis of the modified Pasquill and Gifford formula as given below (Peavy et al., 1985)

$$C_{x,0} = \frac{Q}{\pi u \sigma_y \sigma_z},$$

where $C_{x,0}$ is the difference in pollutant concentration (downwind value−upwind value) (g/m^3), Q is the pollutant emission rate (g/s), π=3.14159, u is the mean wind

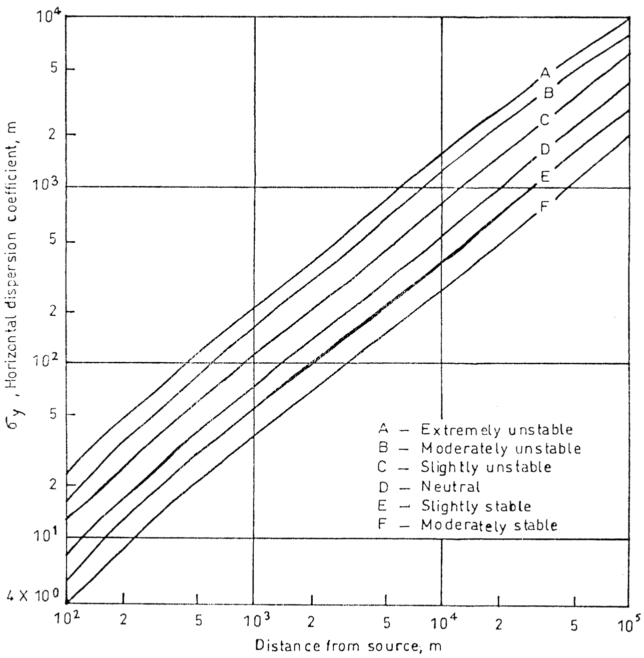

Fig. 3. Lateral diffusion coefficient σ_y vs downward distance from source [source: Davis (1973)].

speed (m/s), σ_y is the horizontal dispersion coefficient, compiled as a function of downwind distance and stability (Fig. 3) σ_z vertical dispersion coefficient, compiled as a function of downwind distance and stability (Fig. 4)

Values of $C_{x,0}$ and u have been generated by field monitoring in the respective mine to determine the emission rate of an activity. However, values of σ_y and σ_z have been taken from graph (relation of σ_y and σ_z with downwind distance from source) prepared by Peavy et al (1985). The two basic factors that influence the movement of pollutants from their points of origin to some other location are 'horizontal wind speed and direction' and 'vertical temperature structure' of the atmosphere. The influence of these parameters can be combined and the joint parameter is then known as 'atmospheric stability' (some representative values for each of the five categories are given in Table 4).

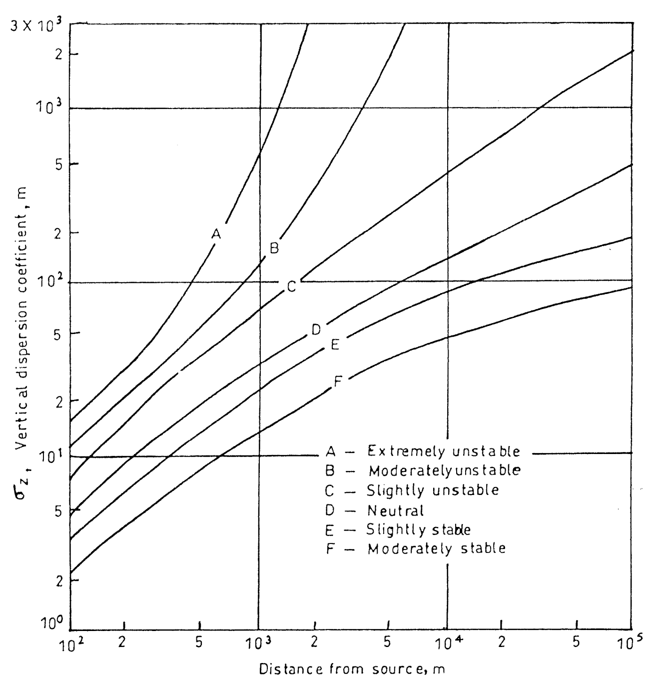

Fig. 4. Vertical diffusion coefficient σ_z vs downward distance from source [source: Davis (1973)].

2.5. Development of empirical formulae

The emission rate calculated for different mining activities along with the key influencing parameters for ten mines have been statistically analysed following Snedecor and Cochran (1967). Empirical formulae have been developed to calculate the emission rate from various mining activities by considering the major influencing parameters for individual activities. The following steps have been executed in sequential order to derive the empirical formulae:

1. The data set with regards to each activity has been segregated and tabulated keeping in view the different major parameters influencing the emission rate due to that particular activity.
2. Each data set has been scanned to find out the degree of biasness of the respective set keeping in view the boundary conditions of the parameters. The set of data not confirming to the boundary conditions has been rejected.
3. Based on limiting boundary conditions for each parameter equation sets have been selected. Some of the examples are given in Table 5.
4. Permutation and combination between all the equations for each of the parameters for a particular activity have been done to arrive at the best fit equation, using an indigenously developed statistical software.
5. Finally, the accepted values of the empirical constants (up to two places of decimal) of the best fit equations have been evaluated from the actual data using search method (Newton–Jacobian method). In case of power coefficient, the values have been restricted up to a single place after decimal where ever possible because it has been found to be sufficient to arrive at a correlation coefficient of >0.9 between actual measured value and predicted value as generated by the empirical equations.

2.6. Validation study

Separate emission inventory study has been carried out at Rajpura opencast coal mine to validate the developed empirical formula for each mining activity.

Table 4
Atmospheric stability categories for use in dispersion modelling

Surface wind speed at 10 m height (m/s)	Insolation stability class[a]				
	Day			Night	
	Strong[b]	Moderate[c]	Slight[d]	Thinly overcast or more than half cloud[e]	Clear to less than half cloud
< 2	A[f]	A	B	–	–
< 2–3	A-B	B	C	E	F
< 3–5	B	B–C	C	D	E
< 5–6	C	C–D	D	D	D
> 6	C	D	D	D	D

[a] Insolation amount of sunshine.
[b] Sun $> 60^o$ above horizontal; sunny summer afternoon; very convective.
[c] Summer day with few broken clouds.
[d] Sunny fall afternoon; summer day with broken low clouds; or summer day with sun from 15^o to 35^o with clear sky.
[e] Winter day.
[f] Class A indicates the greatest amount of spreading under the most unstable atmospheric conditions, where as class F indicates the least amount of spreading under the most stable atmospheric conditions.

Table 5
Examples of empirical equations considered for the evaluation

Parameters	Boundary conditions	Equations considered to satisfy boundary conditions
m=Moisture content(%)	m=0, E=α	E=Al[n(101)/ ln(m+1)−1]
E= Emission rate	m=100, E=0	$E=A[e^{\{B(100-m)/m\}}-1]$
		$E=A[(100-m)/m]^B$
s=Silt content(%)	s=0, E=0	$E=A[\ln(101)/\ln(101-s)-1]$
E=Emission rate	s=100, E=α	$E=A[e^{\{B.s\ /\ (100-s)\}}-1]$
		$E=A[s/(100-s)]^B$
Other parameters whose curves on X–Y passes through origin	x=0, y=0	$y=A\ x^B$
	x=α, y=α	$y=x/(A+Bx)$
Parameters having multiplicative effect	x=0, y=0	$y=A\ \ln(x+1)$
		$y=A(e^{Bx}-1)$
	x=α, y=α	$y=A\ x^B$
		$y=x/(A+Bx)$
Parameters having additive effect	x=0, y=A	$y=Ae^{Bx}$
	x=α, y=α	$y=A+Bx$

The emission rate measured for different mining activities has been compared with the calculated value derived from the empirical formula for each activity. The results have been statistically analysed to validate the accuracy of the developed formulae (Snedecor and Cochran, 1967).

Similarly, modelling exercise has been carried out for the mine by applying the calculated emission rate from the derived empirical formula for each mining activity as an input to the model alongwith micro-meteorological parameters and other details. The predicted concentration of SPM at the selected receptor locations has been compared with the measured data at the field for validation study. The present study sites are almost plain (flat terrain) and activities are localized but all three types of sources namely point, area and line are present. Therefore, the FDM model has been used for the validation study.

Baseline air quality data has been generated for the winter season and modelling has also been carried out for this season to validate the developed empirical formulae. FDM is a computerized Gaussian plume dispersion model specifically developed by USEPA for the estimation of particulate concentrations (USEPA, 1995b). The basic model incorporates a detailed deposition routine based on the equations of Ermak (1977). The sources may be point, line or area. The model can process up to 1200 receptors and upto 121 sources. The line and area source algorithms are based on algorithms of the CALINE3 model (California Department of Transportation, 1979). FDM employs an advanced gradient transfer particle deposition algorithm (Horst, 1977; Hanna et al., 1982).

The average of winter season hourly micro-meteorological parameters for 24 h have been assigned as an input to the model. Utilizing the plan of the Rajpura mine (for locating different activities), the emission rate of each activity and meteorological data, FDM has been run. Emission sources have been classified into three categories namely point, line and area. All these sources are numbered and shown in Fig. 5. Numbers 1–48 represent line source (1–26 transport roads and 27–48 haul roads), numbers 49–56 are area source (49–50 exposed overburden dump, 51 stock yard, 52 workshop and 53–56 exposed pit faces) and numbers 57–63 represent point sources (57–58 drilling points, 59 coal handling point, 60 coal unloading point, 61 overburden loading point and 62–63 overburden unloading points). Therefore, a total of 48 line sources, eight area sources and seven point sources have been defined for input to the model. Line sources have been broken into small segments to convert the curvilinear source to line sources and areas sources have been broken into small area sources to avoid exceeding the maximum width-length ratio of 1:5. Emission rate has been assigned to each activity as per the calculation from developed empirical formula for each mining activities. A total of nine receptor locations (A1–A9, as demarcated in Fig. 5) have been selected at which ground level SPM concentration has been predicted and also actual field measurement has been taken. The model predicts the pollutant concentration at the selected receptor locations and these values are compared with the measured values generated during the field study at that particular site.

2.7. Limitations

An emission inventory study has been carried out only during winter season (1997–98) to find out the worst possible emission rate. This emission rate would be useful to predict the maximum concentration of pollutants by modelling and the data may be used for greenbelt design and air pollution management. Input data on emission rates from various activities have been calculated based on the assumption that one activity in a mine does not influence other activities. The empirical formula developed for each activity is based on field study at seven opencast coal and three iron ore mines, and the average of three readings at each monitoring station. The sink potentials of the pollutants at the field like forests, green cover, obstructions by buildings and dumps, etc. could not be taken into account in the developed empirical formulae and also during air quality modelling. FDM model used for air quality modelling cannot include terrain features, and the model can be used only for local scale predictions (USEPA, 1995). However, this model

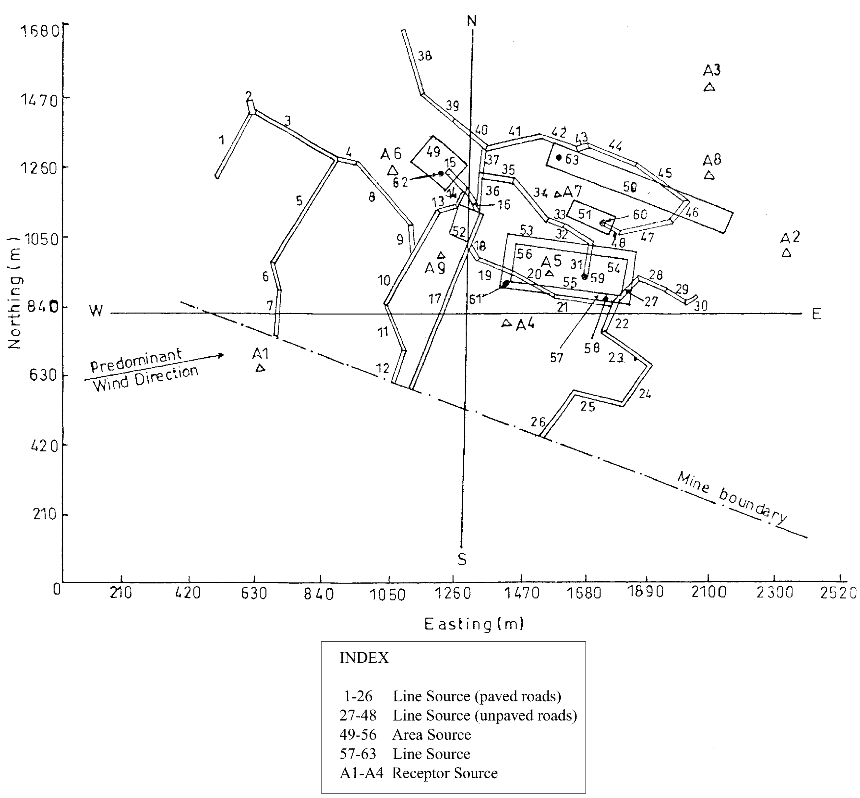

Fig. 5. Schematic diagram of emission sources for the Rajpura mine.

Table 6
SPM emission inventory at the study sites

Activity	Emission rate									
	Sasti	Lakhanpur	Belpahar	Ananta	Jagannath	Block II	Kusunda	Noamundi	Bicholim	Kirlepale
Drilling g/s	0.3825	0.6257	0.4910	0.5919	0.5461	0.4422	0.4151	0.3433	–	–
Overburden loading g/s	0.4186	0.4176	0.5176	0.4241	0.5702	0.4867	0.4596	0.3317	0.3184	0.2991
Mineral loading g/s	0.4872	0.5733	0.5617	0.5891	0.5908	0.5783	0.5402	0.2317	0.2233	0.1963
Haul road g/s/m	0.0132	0.0085	0.0090	0.0094	0.00973	0.0144	0.0112	0.00775	0.0072	0.0078
Transport road g/s/m	0.0140	0.00844	0.0115	0.0106	0.00983	0.0146	0.0119	0.0072	0.0070	0.0063
Overburden unloading g/s	1.1103	1.2775	1.2249	1.254	1.3940	1.2740	0.8299	0.7047	0.7651	0.6529
Mineral unloading g/s	0.7618	0.6164	1.1500	0.5191	0.5354	0.7333	0.5795	0.5354	0.5036	0.5118
Exposed OB dump g/s/m^2	0.00003675	0.0000387	0.0000393	0.0000363	0.0000365	0.0000377	0.0000354	0.0000282	0.0000257	0.00002713
Stock yard g/s/m^2	0.0002066	0.000160	0.0001869	0.000216	0.000238	0.000237	0.0001763	0.0001584	0.000176	0.00014435
Screening plant g/s/m^2	0.000647	0.000432	0.000428	0.000514	0.0005295	0.000572	–	0.0004318	0.0004445	0.0003765
Workshop g/s/m^2	0.000111	0.000082	0.0000628	0.000100	0.000051	0.000100	0.000088	0.00007375	0.00007575	–
Exposed pit surface g/s/m^2	0.00001528	0.0000154	0.0000160	0.0000149	0.0000134	0.0000129	0.0000155	0.0000118	0.00001195	0.0000114
Overall mine g/s	21.984425	20.5121	25.7117	20.3444	18.2560	24.8768	16.15478	4.5434	5.1496	4.4688

Table 7
SPM emission inventory at Rajpura mine

Activity	SPM conc. (μg/m^3)				Wind velocity, u (m/s)	Dispersion coefficient		Distance of measurement (m)	Emission rate	
	DN1 (Min)	DN2 (Max)	UP	$C_{x,0}$ (DN2-UP)		sy	sz		Unit	Value
Drilling	1340	1758	1179	579	2.6	14	7.5	100	g/s	0.4966
Overburden loading	1234	1660	1262	398	2.6	18	10	150	g/s	0.5852
Mineral loading	1648	2092	1640	452	2.6	18	10	150	g/s	0.6646
Haul road	1963	2496	1176	1322	3.3	14	7.5	100	g/s/m	0.0144
Transport road	2015	2605	1163	1442	3.3	14	7.5	100	g/s/m	0.0157
Overburden unloading	1195	1605	1226	379	2.3	24	16	250	g/s	1.0517
Mineral unloading	1438	1897	1401	496	2.3	18	10	150	g/s	0.6451
Exposed overburden dump	1030	1387	913	474	2.6	24	16	250	g/s/m^2	0.0000464
Stock yard	1482	1872	1655	217	2.6	24	16	250	g/s/m^2	0.000252
Screening plant	Not present									
Workshop	1062	1478	955	523	1.8	24	16	250	g/s/m^2	0.0001135
Exposed pit surface	1015	1357	1028	329	1.8	24	16	250	g/s/m^2	0.0000204
Overall mine	469	713	307	406	2.9	95	60	1000	g/s	21.0838

offers improved performance over both the Industrial Source Complex Model (USEPA, 1995) and also the Point, Area and Line (PAL 2) source model (CMRI, 1998). Emission of SPM from the combustion of diesel fuel and blasting has not been quantified nor modelled.

3. Results and discussion

3.1. Emission inventory

The emission data for each activity of all the study sites have been presented in Table 6. SPM concentration has been measured at three locations viz. one at upwind direction (UP) and two in downwind direction (i.e. DN1 and DN2 for minimum and maximum SPM concentration in the downwind direction, respectively). The distance of measurement in the case of most of the activities has been found to vary between 100 and 150 m, the exceptions being exposed overburden dump, exposed pit surface, stockyard, screening plant and workshop where the measurements have been taken at a distance of ca. 250 m from the centre of the area/activity considering their large size. And in case of the over all mine the instruments have been installed at ca 1000 m from the centre of the mine. The value of horizontal (σ_y) and vertical (σ_z) dispersion coefficient has been calculated as per the methodology described earlier. The maximum possible emission rate for different activities has been calculated as per the difference in measured values of SPM concentration ($C_{x,0}$) between downwind (maximum concentration) and upwind directions (UP). SPM emission inventory for each activity of Rajpura mine is given in Table 7. As mentioned earlier, emission rates of SO_2 and NO_x are negligible for most activities and hence, the same has been calculated for the whole mine (Table 8). Parameters like moisture content and silt content of various materials as well as effecting emission rate of respective activity have been measured in the field. An example (Rajpura mine) of the average value of each influencing parameter for all the activities has been presented in Table 9. It has been observed that coal and ore handling plants, and haul and transport roads are the major sources of emission from the mines. Due to occasional rain during the study period at almost all the mines, variation in moisture and silt content of different materials and thereby emission rates for various activities have been observed. These key influencing parameters and measured emission rate for each mining activity have been utilized for the development of empirical formulae.

Table 8
SO_2 and NO_x emission inventory for different mines

Name of the mine	SO_2 emission rate (g/s)	NO_x emission rate (g/s)
Sasti	0.8334	0.5770
Block II	1.3631	0.6816
Kusunda	0.8835	0.5469
Lakhanpur	1.3471	0.8572
Belpahar	1.2785	0.7813
Ananta	1.1757	0.7156
Jagannath	0.9450	0.6873
Rajpura	0.7732	0.3383
Noamundi	0.0390	0.4680
Bicholim	0.0251	0.4271
Kirlepale	0.0178	0.1424

3.2. Development of the empirical formulae

Based on the procedure described earlier, a set of 12 different empirical formulae has been finally selected to calculate SPM emission rate from each mining activities (Table 10). The formulae have been developed for the following opencast coal mining activities and locations:

1. drilling;
2. overburden (OB) loading;
3. coal loading;
4. haul road;
5. transport road;
6. overburden loading;
7. coal unloading;
8. exposed overburden dump;
9. stock yard;
10. coal handling plant;
11. workshop; and
12. exposed pit surface.

Empirical formula has also been developed for the determination of the SPM emission rate from the whole mine. It has already been discussed that emission of gaseous pollutants (SO_2 and NO_x) has been found to be negligible for individual activities. Therefore, empirical formulae have been developed for overall mine only for the estimation of SO_2 and NO_x as given in Table 10.

3.3. Validation

3.3.1. Field measurements

Field measurement and calculated values for Rajpura mine are listed in Table 11. It has been found that accuracy between field measured value and calculated value from empirical formulae varies between 77.2 and 80.4%; this indicates fairly good accuracy.

3.3.2. Air pollution modelling

Average (whole study period) hourly micro-meteorological data for winter season (1997–98) are represented in the Table 12. SPM concentrations at nine receptor locations have been predicted from the modelling exer-

Table 9
SPM emission of Rajpura mine site (values calculated using EmissCalc)

Activity	Source type	Parameters	Values
Drilling	Point	Moisture content (%)	8.3
		Silt content of cuttings (%)	36
		Wind speed (m/s)	2.1
		Hole diameter (mm)	150
		Frequency of drilling (No. of holes/day)	11
		Emission rate (g/s)	0.3879
Overburden loading	Point	Moisture content (%)	8
		Silt content of loading material (%)	13.0
		Wind speed (m/s)	2.4
		Drop height (m)	1.3
		Size of loader (m^3)	4.6
		Frequency of loading (no./h)	23
		Emission rate (g/s)	0.4591
Coal loading	Point	Moisture content (%)	7.9
		Silt content of loading material (%)	9.2
		Wind speed (m/s)	2.1
		Drop height (m)	0.8
		Size of loader (m^3)	4.6
		Frequency of loading (no./h)	22
		Emission rate (g/s)	0.5255
Haul road	Line	Moisture content of haul road dust (%)	18.5
		Silt content of haul road dust (%)	32.0
		Wind speed (m/s)	3.1
		Average vehicle speed (m/s)	2.5
		Frequency of vehicle movement (no./h)	11
		Capacity of dumpers (t)	35
		Emission rate (g/s/m)	0.0115
Transport road	Line	Moisture content of transport road dust (%)	16.1
		Silt Content of transport road dust (%)	30.8
		Wind speed (m/s)	3.1
		Average vehicle speed (m/s)	10
		Frequency of vehicle movement (no./h)	16
		Emission rate (g/s/m)	0.0126
Overburden unloading	Point	Moisture content of unloading material (%)	8.0
		Silt content of unloading material (%)	14.3
		Wind speed (m/s)	1.9
		Drop height (m)	12.5
		Capacity of unloader (t)	35
		Frequency of unloading (no./h)	8
		Emission rate (g/s)	0.8305
Coal unloading	Point	Moisture content of unloading material (%)	7.8
		Silt content of unloading material (%)	9.8
		Wind speed (m/s)	2.0
		Drop height (m)	2.5
		Capacity of dumper (t)	35
		Frequency of unloading (no./h)	6
		Emission rate (g/s)	0.4983
Exposed overburden dump	Area	Moisture content of dump material (%)	9.1
		Silt content of dump material (%)	7.2
		Wind speed (m/s)	2.5
		Area of active dump (km^2)	0.032
		Emission rate ($g/s/m^2$)	0.0000359
Stock yard	Area	Moisture content of material (%)	7.6
		Silt content of material (%)	12.0
		Wind speed (m/s)	1.8
		Capacity of unloader (t)	35
		Size of loader(m^3)	4.6
		Frequency of unloading (no./h)	3.0
		Frequency of loading (no./h)	12.0
		Emission rate ($g/s/m^2$)	0.0002002

(*continued on next page*)

Table 9 (*continued*)

Activity	Source type	Parameters	Values
Coal handling plant (CHP)	Area	Moisture content of coal in the coal handling plant (%)	*CHP IS*
		Silt content of material (%)	*NOT PRESENT*
		Wind speed (m/s)	
		Area (km^2)	
		Emission rate (g/s/m^2)	-
Workshop	Area	Moisture content of ground surface dust (%)	13.0
		Silt content of ground surface dust (%)	32.0
		Wind speed (m/s)	1.7
		Area (m^2)	10000
		Emission rate (g/s/m^2)	0.0000912
Exposed pit surface	Area	Moisture content of surface (%)	6.6
		Silt content of surface material (%)	8.8
		Wind speed (m/s)	1.0
		Area (km^2)	0.0350
		Emission Rate (g/s/m^2)	0.0000162
Overall mine	Area	Wind speed (m/s)	2.4
		Coal production (Mt/Yr)	1.0
		OB handling (Mm^3/Yr)	3.5
		Leasehold area (km^2)	1.74
		Emission rate (g/s)	16.4951

Table 10
Empirical formula for emission rate of each activity[a]

Activity	Empirical equation
Drilling	E=0.0325 $[\{(100-m)su\}/\{(100-s)m\}]^{0.1}$ $(df)^{0.3}$
Overburden loading	E=$[0.018\{(100-m)/m\}^{1.4}$ $\{s/(100-s)\}^{0.4}(uhxl)^{0.1}]$
Coal/mineral loading	E=$[\{(100-m)/m\}^{0.1}$ $\{s/(100-s)\}^{0.3}$ $h^{0.2}$ $\{u/(0.2+1.05u)\}\{xl/(15.4+0.87xl)\}]$
Haul road	E=$[\{(100-m)/m\}^{0.8}\{s/(100-s)\}^{0.1}u^{0.3}$ $\{2663+0.1(v+fc)\}10^{-6}]$
Transport road	E=$\{(100-m)s\}/\{m(100-s)\}]^{0.1}u^{1.6}\{1.64+0.01(v+f\}\}$ 10^{-3}
Overburden unloading	E=$[1.76h^{1/2}\{(100-m)/m\}^{0.2}$ $\{s/(100-s)\}^{2}$ $u^{0.8}$ $(cy)^{0.1}$ $]$
Coal/mineral unloading	E=$0.023[\{(100-m)sh\}/\{m(100-s)\}]^{2}(u^{3}cy)^{0.1}$
Exposed overburden dump	E=$[\{(100-m)/m\}^{0.2}$ $\{s/(100-s)\}^{0.1}\{u/(2.6+120u)\}\{a/(0.2+276.5a)\}]$
Stock yard	E=$\{(100-m)/m\}^{0.1}\{s/(100-s)\}\{u/(71+43u)\}[\{cy/(329+7.6cy)\}+\{lx/(30+900lx)\}]$
Coal handling plant	E=$[\{(100-m)/m\}^{0.4}\{a^{2}s/(100-s)\}^{0.3}$ $\{u/(160+3.7u)\}]$
Workshop	E=$[0.064\{(100-m)/m\}^{1.8}$ $\{as/(100-s)\}^{0.1}\{u/(0.01+5u)\}10^{-4}]$
Exposed pit surface	E=$[2.4\{(100-m)/m\}^{0.8}\{as/(100-s)\}^{0.1}$ $\{u/(4+66u)\}10^{-4}]$
Overall mine (for SPM)	E=$[u^{0.4}a^{0.2}\{9.7+0.01p+b/(4+0.3b)\}]$
Overall mine (for SO_2)	E=$a^{0.14}\{u/(1.83+0.93u)\}\cdot[\{p/(0.48+0.57p)\}+\{b/(14.37+1.15b)\}]$
Overall mine (for NO_x)	E=$a^{0.25}\{u/(4.3+32.5u)\}[1.5^{p}+\{b/(0.06+0.08b)\}]$

[a] Note: parameters and units and symbols used are: moisture content (%), *m*; silt content (%), *s*; wind speed (m/s), *u*; hole diameter (mm), *d*; frequency (No. of holes/day), *f*; drop height (m), *h*; size of loader (m^3), *l*; average vehicle speed (m/s), *v*; capacity of dumpers/unloader (t), *c*; area (km^2), *a*; frequency of unloading (no./h), *y*; frequency of loading (no./h), *x*; coal/mineral production (Mt/yr), *p*; OB handling (mm^3/yr), *b*; emission rate (g/s), *E*.

cise. The predicted values at receptor locations have been added to regional background level (i.e. 365 μg/m^3) to get the total predicted 24 hourly average SPM concentration. Regional background SPM concentration is the minimum of the 24 hourly average monitored data in the upwind direction. The predicted and observed SPM concentrations at the receptor locations for different mines are listed in Table 13.

The performance of FDM model has been evaluated through a set of statistical parameters. The various statistical parameters calculated are correlation coefficients, regression coefficients and index of agreement. The correlation coefficient provides an idea about how far the measured values are related to predicted values. Regression coefficients represent the status of best fit line between measured and predicted values. The index of agreement shows the degree to which the model predictions are error free.

The correlation coefficient value for FDM has been calculated to be 0.894. It shows a fairly good agreement between measured and predicted values. Linear regression coefficients *a* and *b* have been calculated to

Table 11
Comparison of emission rate of each mining activity between measured and calculated values for Rajpura mine

Activity	Unit	Measured value	Calculated value	Accuracy (%)
Drilling	g/s	0.4966	0.3879	78.1
Overburden loading	g/s	0.5852	0.4591	78.4
Coal loading	g/s	0.6646	0.5255	79.1
Haul road	g/s/m	0.0144	0.0115	79.9
Transport road	g/s/m	0.0157	0.0126	80.3
Overburden unloading	g/s	1.0517	0.8305	79.0
Coal unloading	g/s	0.6451	0.4983	77.2
Exposed OB dump	$g/s/m^2$	0.0000464	0.0000359	77.4
Stock yard	$g/s/m^2$	0.000252	0.0002002	79.4
Workshop	$g/s/m^2$	0.0001135	0.0000912	80.4
Exposed pit surface	$g/s/m^2$	0.0000204	0.0000162	79.4
Overall mine (SPM)	g/s	21.0838	16.4951	78.2

Table 12
Hourly micro-meteorological data for model input — Rajpura Mine

Hour (IST)	Wind direction (from) (0)	Average wind speed at 10 m height (m/s)	Stability class (Pasquill–Gifford)	Mixing height (m)	Temperature (K)
00	236	0.3833	F (6)	48	288.77
01	225	0.3694	F (6)	56	288.37
02	229	0.4028	F (6)	44	288.08
03	227	0.3750	E (3)	60	287.67
04	220	0.3750	D (4)	49	287.67
05	222	0.3528	C (3)	65	287.04
06	216	0.3528	B (2)	76	287.30
07	201	0.4722	B (2)	58	289.71
08	186	0.7556	B (2)	61	292.42
09	193	0.9583	B (2)	109	294.49
10	191	1.0722	B (2)	261	296.01
11	205	1.2694	A (1)	424	297.07
12	206	1.3306	A (1)	425	297.84
13	202	1.2667	A (1)	405	298.23
14	218	1.2083	A (1)	428	298.23
15	221	1.0222	A (1)	448	297.70
16	237	0.6861	A (1)	322	275.64
17	246	0.5222	A (1)	473	293.60
18	254	0.5306	B (2)	238	292.33
19	256	0.4944	C (3)	307	291.55
20	255	0.5111	D (4)	139	290.97
21	242	0.4194	E (5)	77	290.35
22	239	0.4139	E (5)	63	289.66
23	235	0.3028	F (6)	59	289.06

be 0.963 and 51.957, respectively. The values of index of agreement show the extent to which the model performs. The average index of agreement value for FDM has been calculated as 0.79 which indicates that the prediction by FDM model is 79% accurate. The variation between measured and predicted values may be due to non-accountability of emission from various other anthropogenic sources and activities, such as blasting, domestic use of fuels, transportation network, etc. Overlapping of emission from different activities, and non-consideration of sinks, like buildings, dumps, vegetation, forests, green belts, etc. as well as protection measures like water sprinkling, dust arrestors etc. are also the major causes for difference between predicted and measured values of SPM concentrations (Hosker, 1974; Slinn, 1982).

3.4. Software

An user friendly and totally menu driven software named 'EmissCalc', has been developed on the 'Dbase/FoxPro' platform to calculate the emission rates for various mining activities. The software generates the expected emission load due to the different opencast coal

Table 13
Predicted and observed values of SPM by FDM model for Rajpura mine

Receptor location code	Measured SPM concentration (μg/m^3)	Predicted SPM concentration (μg/m^3)
A1	469	502
A2	713	663
A3	365	459
A4	985	863
A5	1015	1122
A6	942	811
A7	1002	1147
A8	1030	905
A9	1040	894

mining operations on receipt of data related to various influencing parameters as mentioned earlier. Fig. 6 illustrates the flow chart of the software. [The software is being marketed by CMRI, Dhanbad, 826001 (Jharkhand), India.]

The opening menu of the software receives information about the emission types, for example, particulate or gaseous. In the next sub-level the menu selection decides the particular operation for which the emission rate to be generated in case of particulate emission. While in case of gaseous emission, it will allow the user to select between emission generated for SO_2 and NO_x. On receipt of all the input parameters and subsequent to confirmation about the accuracy of the data; the emission load is generated and all the input as well as the generated data are stored in the databases. The data can be printed only on express request by the users. Thereafter an ASCII (∗.txt) data file is created from the data base which is automatically emptied. The ASCII file can be retained or deleted as per the choice of the user.

It should be noted here that the database is automatically initialized every time to save precious system resources. The option to retain the ASCII file has been provided so that the user is able to use the same for some other purposes. In case the user wishes to retain the ASCII then care must be taken to delete all such files before using the software once again, otherwise the current set of data will be appended at the end of the old file.

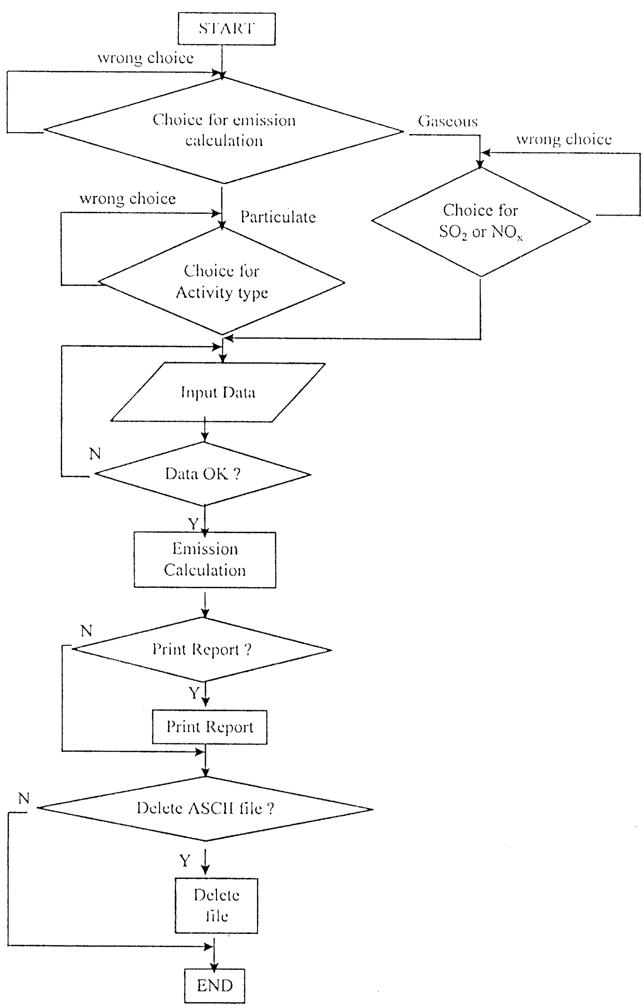

Fig. 6. Flow diagram for emission calculation using ‘EMISSCALC’.

4. Conclusions

The study at seven opencast coal and three iron ore mines has indicated that suspended particulate matter is the major constituent of emission, whereas emissions of SO_2 and NO_x from most of the mining activities are negligible. A set of 12 empirical formulae has been developed by considering the major influencing parameters to calculate SPM emission rate from each opencast mining activity. Empirical formulae have also been developed for the estimation of SPM, SO_2 and NO_x emission rates for the whole mine. An user friendly software to calculate emission rate has also been developed. To find out the accuracy of the developed formulae, the correlation coefficients between the measured values and calculated values for Rajpura mine have been determined. The accuracy was found to vary from 77.2 to 80.4%.

The variation between measured and FDM predicted values has been calculated for Rajpura mine. The average accuracy of 79% has been observed by FDM. This is because, in real life there may be emission from other activities like blasting, barren areas, non-mining sources viz. domestic, nearby transportation network, other industry, obstructions and sink potential of the area. The present study has been conducted for 10 opencast mines only. Therefore, similar studies should also be conducted for other mines to determine how the emission factor and emission formula can be further modified.

With the development of the empirical formulae to calculate the emission rate for each activity, the prediction of air pollution is possible even before the commencement of any mining project and effective mitigative measures can be designed at the planning stage. Therefore, these results may also be utilized for visualizing the future environmental scenario and local level decision making with respect to air environment for granting permission to exploit minerals in a more rational and realistic fashion.

Acknowledgements

The authors are grateful to the following: the Director, Central Mining Research Institute (CMRI), Dhanbad for giving permission to publish this paper; the scientists and other members of the Environmental Management Group of CMRI for their help during field monitoring; and the mine management of Mahanadi Coalfields Ltd, Eastern Coalfields Ltd, Bharat Cooking Coal Ltd, Western Coalfields Ltd, Tata Iron and Steel Company and DEMPO Mining Corporation for providing necessary facilities and cooperation during the field study. Financial support from the Ministry of Environment and Forests, the Government of India, is also gratefully acknowledged.

References

California Department of Transportation 1979. CALINE3 — A Versatile Dispersion Model for Predicting Air Pollutant Levels Near Highways and Arterial Street, No. FAWA/CA/TL-79/23. Office of Transportation Laboratory Department of Transportation, State of California, Sacramento, CA.

Central Mining Research Institute (CMRI) 1998. Determination of Emission Factor for Various Opencast Mining Activities, GAP/V/9/MOEF/EMG. Ministry of Environment and Forests, Government of India, New Delhi, India.

Cowherd, D. Jr, 1982. Fugitive Emission Factor Update for AP-42 Final Report. US Environmental Protection Agency, Industrial Research Laboratory, Research Triangle Park, NC.

Davis, M.L., 1973. Air Resources Management Promer, ASCE.

Ermak, D.L., 1977. An analytical model for air pollutant transport and deposition from a point source. Atmospheric Environment 11, 231–237.

Hanna, S.R., Briggs, G.A., Hosker, R.P. Jr, 1982. Handbook on Atmospheric Diffusion, DOE/TIC-11223. Technical Information Center, US Department of Energy, Washington, DC.

Herrmann, P., Hanel, G., 1997. Winter time optical properties of atmospheric particle and weather. Atmospheric Environment 31 (24), 4053–4062.

Horst, T.W., 1977. A surface depletion model for deposition from a Gaussian Plane. Atmospheric Environment 11, 41–46.

Hosker, Jr., R.P., 1974. Estimation of Dry Deposition and Plume Depletion Over Forests and Grassland. In: Proceedings of International Atomic Energy Association on the Physical Behaviour of Radioactive Contaminants in the Atmosphere, Vienna, pp. 291–309.

Jones, T., 1993. The role of environmental impact assessment in coal production and utilisation. Natural Resource Forum 17 (3), 170–180.

Kapoor, R.K., Gupta, V.K., 1984. A pollution attenuation coefficient concept for optimization of green belt. Atmospheric Environment 18 (6), 1107–1117.

Kumar, C.S.S., Kumar, P., Deshpande, V.P., Badrinath, S.D., 1994. Fugitive dust emission estimation and validation of air quality model in bauxite mines. In: Khuntia, G.S. (Ed.), Proceedings of International Conference on Environmental Issues in Minerals and Energy Industry, New Delhi, India, pp. 77–81

National Environmental Engineering Research Institute (NEERI), 1993. Workshop on Computer Aided EIA of Industrial Project, Nagpur, India.

Peavy, H.S., Rowe, D.R., Tchobanoglous, G., 1985. Environmental Engineering. McGraw–Hill, New York.

Rao, C.C.V., 1996. Air quality modelling — research needs. In: Dhar, B.B., Charkraborty, M.K., Chaulya, S.K., Singh, R.S (Eds.), Proceedings of Workshop on Air Quality Modelling and Atmospheric Acidification. Commonwealth Science Council, Dhanbad, India, pp. 1–27.

Shannigrahi, A.S., Agrawal, K.M., 1996. An overview on optimal green belt development around industrial project. Indian Journal of Environmental Protection 17 (4), 253–261.

Sinha, S., 1995. Quantification of fugitive particle emission from line source in surface coal mine — an approach. Indian Journal of Environmental Protection 15 (5), 339–343.

Sinha, S., Banerjee, S.P., 1994. A Method for Estimating Fugitive Particulate Emission from Haul Roads in Opencast Coal Mines and Mitigative Measures. In Banerjee, S.P. (Ed.), Proceedings of Second National Seminar on Minerals and Ecology, Dhanbad, India, pp. 217–227

Sinha, S., Banerjee, S.P., 1997. Characterisation of haul road in Indian open cast iron ore mine. Atmospheric Environment 31 (17), 2809–2814.

Slinn, W.G.N., 1982. Predictions for particle deposition to vegetative canopies. Atmospheric Environment 16, 1785–1794.

Snedecor, G.W., Cochran, W.G., 1967. Statistical Methods. Oxford & IBH Publishing Co, New Delhi.

Soni, D.K., Agarwal, A., 1997. Characterisation of dust emission in coal mining activities - case study. Indian Journal of Environmental Protection 17 (11), 80–814.

Stern, A.C., 1968. Air Pollution, Vol.II, second ed. Analysis, Monitoring and Surveying. Academic Press, New York.

USEPA 1995. User's Guide for the Fugitive Dust Model (FDM), vol. I, User's Instruction. Region 10, Seattle, WA.

Viswanathan, D.V., Mishra, S., Satyanarayana, A.N.V., 1995. Climatological atmospheric dilution over India. Indian Journal of Environmental Protection 15 (10), 734–738.