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APPLICATION OF AERMOD MODEL IN AIR QUALITY (PM_{10}) IMPACT ASSESSMENT OF SELECTED OPENCAST MINES IN THE JHARIA COALFIELD, JHARKHAND, INDIA

The study mainly delineates the application of AERMOD to evaluate PM_{10} concentrations for the selected opencast mines in The Jharia coalfield. AERMOD estimated PM_{10} concentration profiles were developed on the basis of evaluated emission rates of salient coal mining activities. While comparing these estimated values with monitored values of PM_{10}, the evaluated indices of agreement were found to be 0.86, 0.84 and 0.88 during winter and 0.94, 0.68 and 0.87 during summer for the Katrasgarh, Muraidih and Rajapur opencast mines, respectively. In a like manner, performance evaluation of AERMOD evaluated concentrations over actual field concentration using a set of five statistical tools, indicated more or less fairly good prediction for both the seasons. Further, USEPA AP-42 based emission factor data for more or less identical mining activities were also used for AERMOD run in order to evaluate PM_{10} profiles. Correlation analysis indicated 71–89% and 62–85% model accuracy for winter and summer, respectively.

1. INTRODUCTION

Generation of dust is an integral part of opencast coal mining. The major activities which lead to deterioration of dust environment are drilling, overburden loading, movement of dumpers and other vehicles in the unpaved haul road, workshop activities, etc. All the three types sources, namely point, area or line sources, are very much prevalent in opencast coal mining. Assessment of environmental impact of an opencast mine demands a detailed insight into its emission sources and quantification of particulate concentrations [1]. Air dispersion modeling has been applied to evaluate the ambient air quality status at particular receptors in number of research studies [2].

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The particulates especially those within 10 µm size (PM_{10}) are inhalable particles and have close association with respiratory diseases like asthma, heart diseases and increased mortality [3, 4]. Mine workers very often suffer from asthma, black lungs, silicosis, asbestosis, berylliosis, inflammation, bauxite fibrosis and siderosis, etc., due to the exposure of particulate matter [5]. There exist a number of research studies indicating relationship of adverse health outcomes with effective exposure level [6, 7]. Further, these particulates are also said to have a significant impact on our climate [8]. Systematic field investigation is necessary to pinpoint higher exposure level on the part of the exposed persons for initiating effective mitigative measures. In this connection, it is to be remembered that systematic monitoring is time consuming and not always feasible. As such, predictive approach for assessment of ambient air pollution gradients has been developed for exposure estimation [9]. Mokhtar et al. [10] used AERMOD to assess the health risk from emissions from a coal-fired power plant.

AERMOD is a steady-state plume model and is designed to evaluate short-range dispersion of air pollutant emissions from point, line and area sources. The U.S. Environmental Protection Agency (EPA) conjointly with the American Meteorological Society (AMS) have developed this dispersion model. AERMOD can efficiently assess the near-source pollutant behavior by incorporating planetary boundary layer turbulence (meteorology) and terrain effects in urban/industrial locations [11]. AERMOD can simulate the dispersion of pollutants in no more than a few minutes and is thus both cost effective and time saving technique to obtain the air quality status of the concerned area [12]. In the present work, AERMOD model was used to predict PM_{10} concentrations within selected opencast mining areas of The Jharia coalfield for winter and summer seasons. The outcome of the model was validated with field monitored concentration database. Besides, a set of five statistical parameters namely fractional bias, geometrical mean bias, normalized mean square error, fraction of data and index of agreement were used for performance evaluation of the model.

2. THE STUDY AREA

The Jharia coalfield (JCF) is well known for its rich coal resources. JCF is situated in Dhanbad and Bokaro districts of Jharkhand, India. This is a sickle shaped basin with its axis trending in the east-west direction and plunging to the west. The southern part of the basin is truncated by the Great Boundary Fault, which structurally guides the Damodar River. JCF is the most exploited coalfield because of available metallurgical grade coal reserves. The total coal reserves of the JCF (Bharat Coking Coal, Ltd. (BCCL) area) are estimated to be 17 077 million t. Further 2340 million t of coal lie within the jurisdiction of Indian Iron and Steel Company (IISCO) and Tata Iron and Steel Company (TISCO). The coal field lies between latitude from 23°39′ N to 23°48′ N and longitudes from 86°11′ E to 86°27′ E. Three opencast mines, namely the Katrasgarh, Muraidih and Rajapur mine, within the the Jharia coalfield were selected (Fig. 1) for the present study.

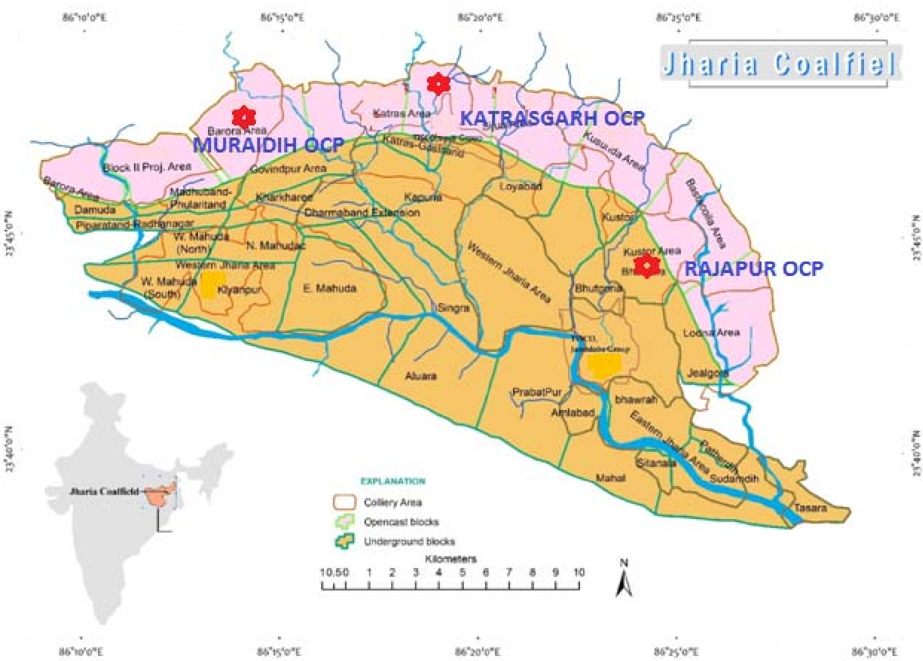

Fig. 1. Location of study area

2.1. THE RAJAPUR OPENCAST MINE

Rajapur lies in the Cluster VII of JCF. The total leasehold area is 207.48 ha. There exist 14 mines within 12 mining lease hold in this Cluster. This Cluster has long history of fire and subsidence. These mines are located in the East Central part of The Jharia Coalfield in the Dhanbad district of the Jharkhand State. It falls between the latitude 23°47′00″ N and 23°43′10″ N, and longitudes from 80°22′54.6″ E to 86°24′45″ E. The area is covered by the Survey of India Topo Sheet No. 73/I/6. The cluster is at a distance of 6.5 km (south) from National Highway (NH-2) which connects the mines with Kolkata and New Delhi. National Highway (NH-32) passes through this cluster. The nearest railway station is Dhanbad at a distance of about 2 km from this cluster. According to the Master Plan of JCF, surface has been rendered unstable in 71 sites due to fire and subsidence. The existing mines within this cluster have a long history of mining activities commencing prior to nationalization of coal mines. Presently mining is continuing from seam II to seam XII both by opencast method and underground bord and pillar method. The coal seams of this cluster lie in the Barakar formation. The alluvium and soil of recent origin and basic and ultra basic intrusive of the post Gondwana period are also present within the area with shallow coal seams up to 500 m deep dipping in the south-west direction. No major faults within the present workings side, but minor faults of throw 2–4 m exist within the lease hold area.

2.2. THE MURAIDIH OPENCAST MINE

The latitude and longitudinal extent of Muraidih opencast mining project (OCP) is 23.94°N, 86.23°E. It lies in the western part of the Jharia Coalfield. The leasehold area of Muraidih is about 717.66 ha and it has a reserve of 115 million t of coal. The Shatabdi OCP was carved out of Muraidih Colliery in the year 2000 and has been once again amalgamated to the Muraidih colliery in April, 2014. 35 coal seams XVIII–I including few local belongings to the Barakar measure have been proved to occur and incrop within the mine. The formation is locally folded into syncline and anticline having a gentle slope towards ESE. The strike of one of the limbs of the folds ESE-WNW and that of others NS. The dip generally varies from 5–10 deg. However, steep dip is observed in the southern part in the vicinity of two major faults F3 and F4.

2.3. THE KATRASGARH OPENCAST MINE

Katrasgarh lies within 23.8°N and 86.29°E. This is situated 10 km west from Dhanbad in the North Central part of the Jharia coalfield. Katras is named after the river Katri. The total leasehold area is 325.00 ha. Seam from VIII B to I has been developed on bord and pillar method. At present IV and above seams are being extracted by opencast method. The present depth of mine is 100 m. There are 5 coal benches and 7 overburden benches running in the mine. The total mineable reserve is 50.952 million t for opencast mine and 9.229 million t for underground mine.

3. METHODS

3.1. AIR QUALITY (PM_{10}) MODELING BY AERMOD

Air quality modeling has been attempted using AERMOD. The AERMOD is basically an Gaussian dispersion model that incorporates the boundary layer theory along with turbulence and dispersion, and terrain features. The air quality model requires two types of input data viz. emission data and meteorological data. Emission rate was evaluated for each commonly occurring activities, i.e., drilling, overburden loading, dumper movement in haul road and workshop activity. The meteorological data for AERMOD include surface data and upper air data. Surface data includes wind direction, wind speed, dry bulb temperature, dew point temperature, total and opaque cloud cover, cloud ceiling height, station pressure, hourly precipitation amount and relative humidity. The data were obtained from the meteorological station nearby the selected mines. AERMOD dispersion model was used to estimate 24 hour average concentrations of PM_{10} for winter (December 2014–February 2015) and summer (April 2014–June 2014) season of the study area. Similarly, U.S. EPA AP-42 emission factors of identical opencast coal mining activities were also used in the model. The model has been run in the ISC-AERMOD View interface. The simulations have been carried out assuming a flat terrain. Drilling and overburden loading were taken as point sources, movement of dumper in haul road as line source and workshop activity as area source.

3.2. AIR QUALITY MONITORING AND DETERMINATION OF MASS CONCENTRATION

Air sampling was done to quantify PM_{10} concentrations in the selected opencast mining areas with the help of Respirable Dust Sampler (Envirotech make) for 24 h study for summer and winter season. The flow rate of the sampler was maintained at 1.1–1.3 m^3/min. The sampling locations were selected as per Bureau of Indian Standards (IS 5182 Part–XIV). EPM 2000 filter paper was used to capture PM_{10} particles. The dust monitoring involves upwind and downwind method of particulate measurement for each mining activity in the coal mine [13]. The filters were weighted under controlled conditions of humidity and temperature using a Mettler AE163 microbalance. The mass concentration was determined by subtracting pre-weight (unexposed) from post-weight (exposed) of the filter.

3.3. PERFORMANCE EVALUATION OF THE MODEL

The model performance was assessed using multiple sample cross-validation and external validation methods. Several validating statistical tools were used to evaluate the model performance [14, 15]. The following statistical validating tools were used on considering relatively small sample size [16, 17]:

- Fractional bias *FB*:

$$FB=\frac{\overline{C_o}-\overline{C_p}}{0.5\left(\overline{C_o}+\overline{C_p}\right)}$$

- Geometrical mean bias *MG*:

$$MG=\exp\left(\overline{\ln C_0}-\overline{\ln C_p}\right)$$

- Normalized mean square error (NMSE):

$$\text{NMSE}=\frac{\overline{C_0-C_p}}{\overline{C_0}\times\overline{C_p}}$$

- Fraction of data that satisfy(FAC2):

$$0.5 \leq \frac{C_p}{C_0} \leq 2$$

- Index of agreement:

$$d = 1 - \left(\frac{\sum_{i=1}^{n} \left(C_p - C_0 \right)^2}{\sum_{i=1}^{n} \left(\left| C_p - \overline{C_p} \right| + \left| C_0 - \overline{C_0} \right| \right)^2} \right)$$

where C_p is a predicted value, C_o – observed value.

The *FB* is a mean bias. A negative value of *FB* indicates model under-prediction. The NMSE is a measure of variance, and a value of 1.0 depicts that difference between predictions and observations is approximately equal to the mean [18]. The over bar indicates means over the runs. In addition to the above measures, the index of agreement (*d*) between predicted and observed values and the number of predictions (FAC2) within a factor of two of the observations are also reported. A perfect model would have the values of *MG* and FAC2 of one and values of *FB* and NMSE of zero. External validation of model performance was also performed by comparing model evaluations to the actual field measured values.

4. RESULTS AND DISCUSSIONS

4.1. WINDROSE DIAGRAM PLOT

The windrose diagram was plotted based on the obtained meteorological data for both winter and summer of the JCF (Fig. 2). The predominant wind direction during winter was found to be N and NW contributing for 35.3% and 15.1% of the time, respectively. The predominant wind speed of 0.5–2.1 m/s was observed. Similarly, the predominant wind direction during summer was found to be N and E-SE contributing for 26.6% and 13.1% of the time, respectively, and the predominant wind speed of 0.5–2.1 m/s was observed.

4.2. MONITORED PM_{10} CONCENTRATION

The actual field particulate matter concentrations varied in the range of 2900–2242 and 2431–4321 μg/m^3 for the Katrasgarh OCP in winter and summer, respectively, 1900–3987

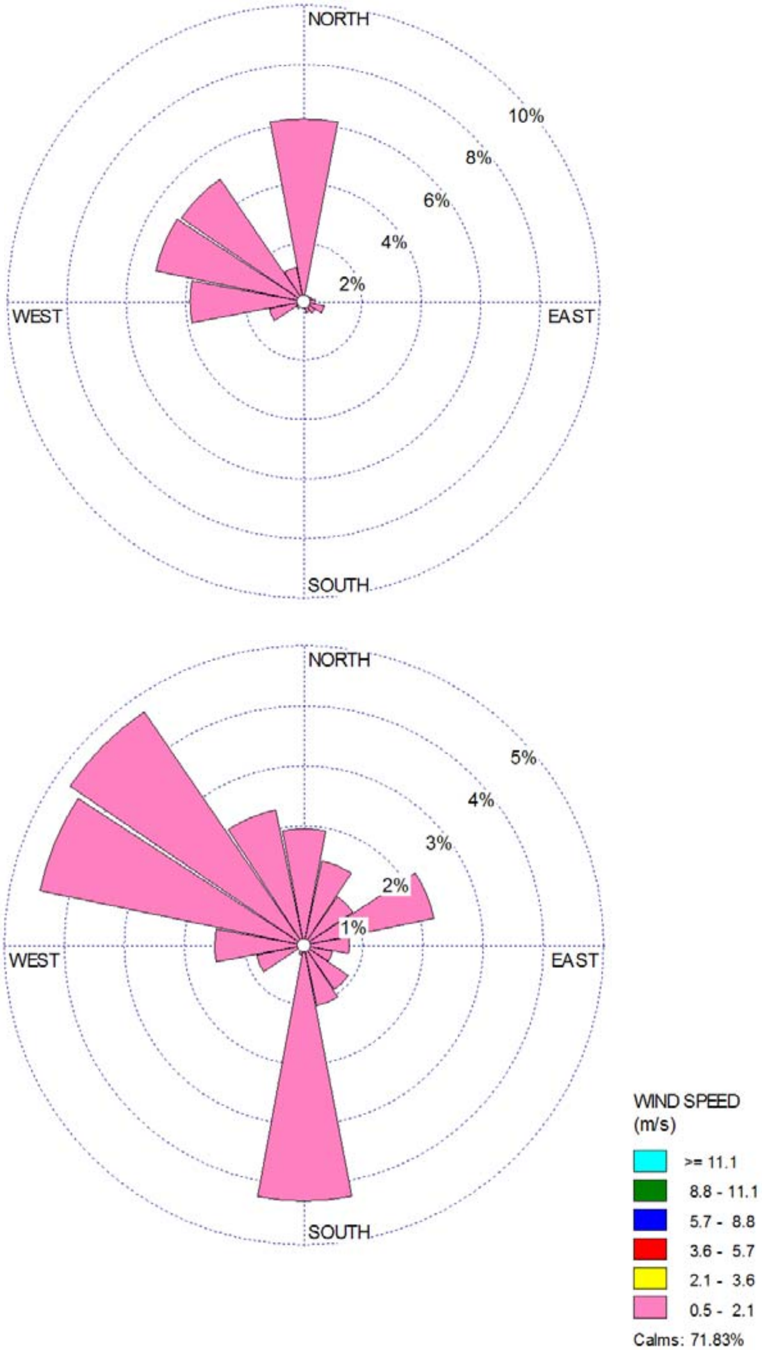

Fig. 2. Windrose diagram for (a) winter and (b) summer season of JCF

and 1500–3500 μg/m^3 for the Muraidih OCP in winter and summer, respectively, 1900 –3998 and 1500–3589 μg/m^3 for the Rajapur opencast mine in winter and summer, respectively. The various mining activities are contributing to such a high concentration of PM_{10} within the opencast coal mine [19–22]. The vehicular activities in haul road are also one of the major contributing sources [23]. In winter all the locations reported higher concentration which may be due to stagnant weather as compared to summer.

4.3. AERMOD EVALUATED PM_{10} CONCENTRATION

The model was run with evaluated emission rate and meteorological databases for the evaluation of expected PM_{10} concentration profiles (in the form of isopleths) of three selected opencast coal mines for both winter and summer seasons as depicted in Figs. 3–5. These isopleths diagrams display the overall PM_{10} profiles within the active mining areas of concerned opencast mines. The maximum concentration levels were observed at the intense mining zone. Subsequent isopleths indicates lower concentration levels.

A number of researchers concentrated on the development of empirical equations of dust generation for different opencast mining activities in Indian conditions [24, 25]. In a similar way, the equations describing PM_{10} emissions for mostly occurring opencast mining activities of the study area were evaluated. This was based on salient factors of the study area, such as moisture content, silt content, number of drill hole, hole diameter, frequency of vehicle/dumper movement, vehicular speed, drop height of shovel, size of loader, area of workshop, meteorological database, etc. as well as activity wise monitored results of PM_{10} emissions. Four sets of equations were developed for each activity for PM_{10}. MATLAB R 2012a software version was used to find the best fit value of the empirical constants. All possible combinations of equations were solved for individual parameters of all the activities to obtain the final emission factor equations. The performance evaluation of these formulated empirical equations was done by a set of five statistical tools – fractional bias, geometrical mean bias, normalized mean square error, fraction of data and index of agreement.

In this connection it is to be mentioned that the U.S. EPA AP-42 database is broad-based. However, due to difference in mine environment, mining equipment, etc. in both the countries the parameters undertaken for emission estimation slightly vary from those of AP-42.

4.4. CROSS-VALIDATED MODEL PERFORMANCE

The calculated *FB* values during the winter season were found to be 0.03, 0.07 and 0.05 for the Katrasgarh, Muraidih and Rajapur OCP, respectively, which displayed that the model estimation for PM_{10} was slightly over-predicting for all the three selected mines. The calculated NMSE values were found to be 0.001, 0.005 and 0.003 for the three mines, respectively.

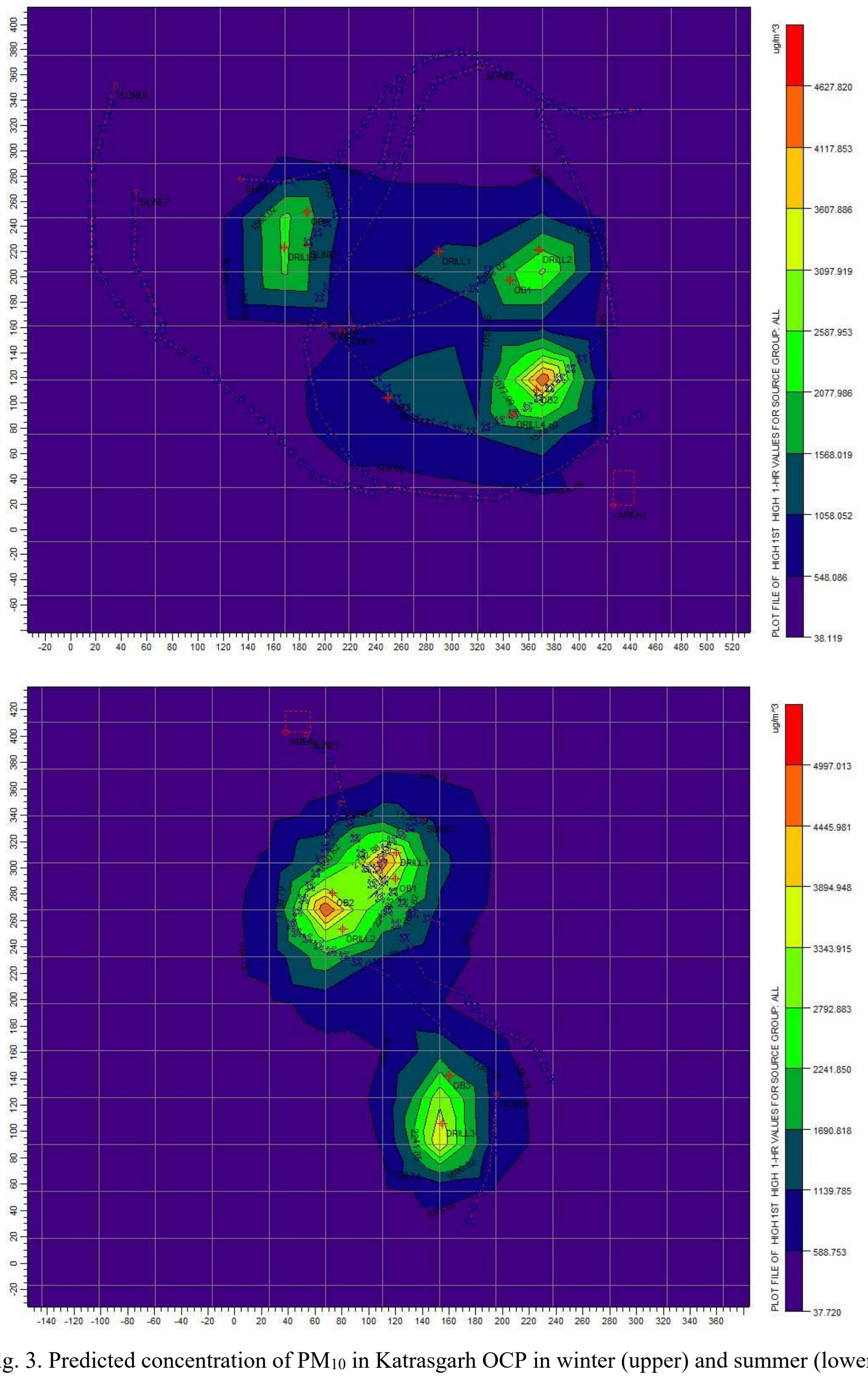

Fig. 3. Predicted concentration of PM_{10} in Katrasgarh OCP in winter (upper) and summer (lower)

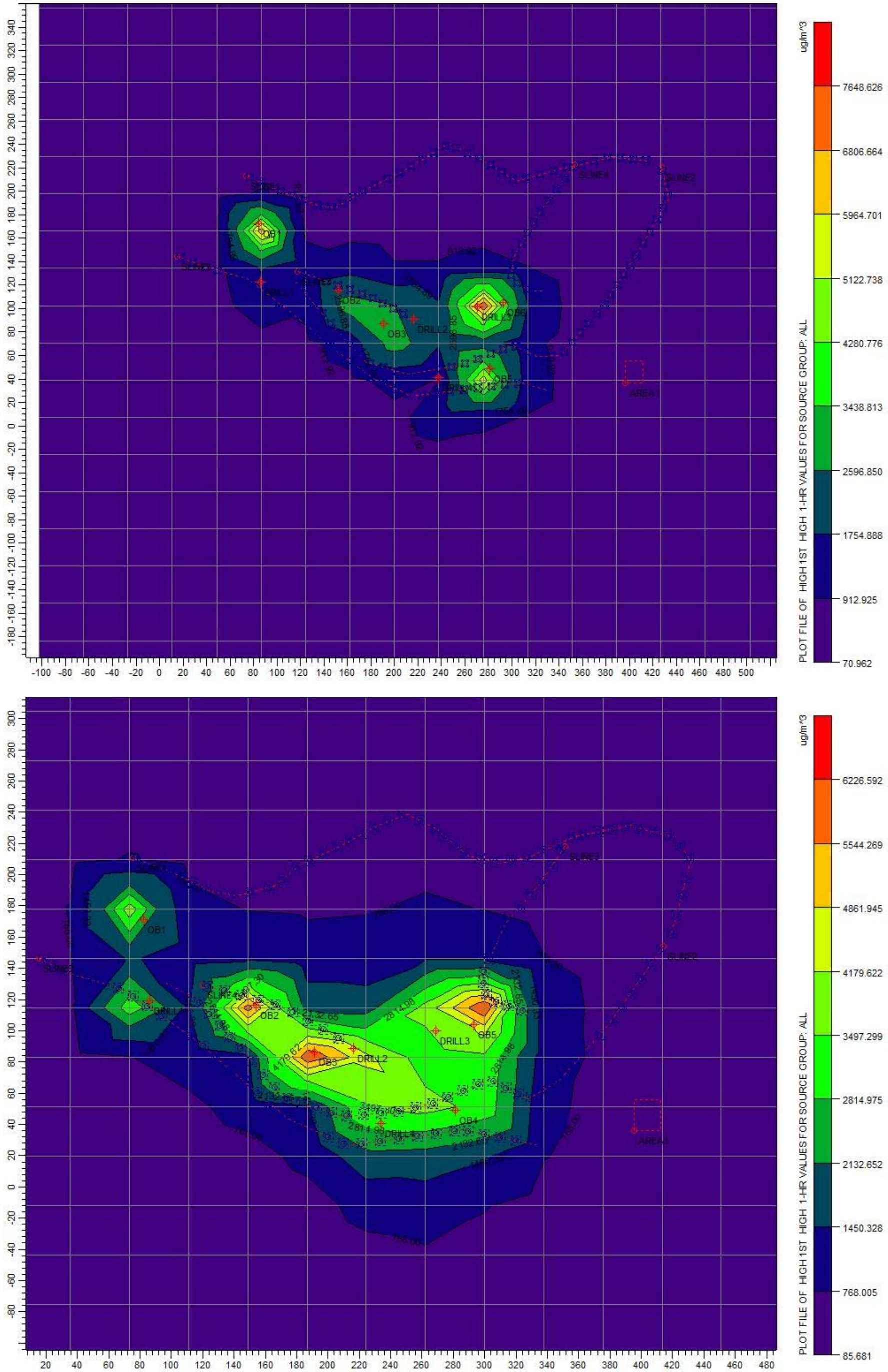

Fig. 4. Predicted concentration of PM_{10} in Muraidih OCP in winter (upper) and summer (lower)

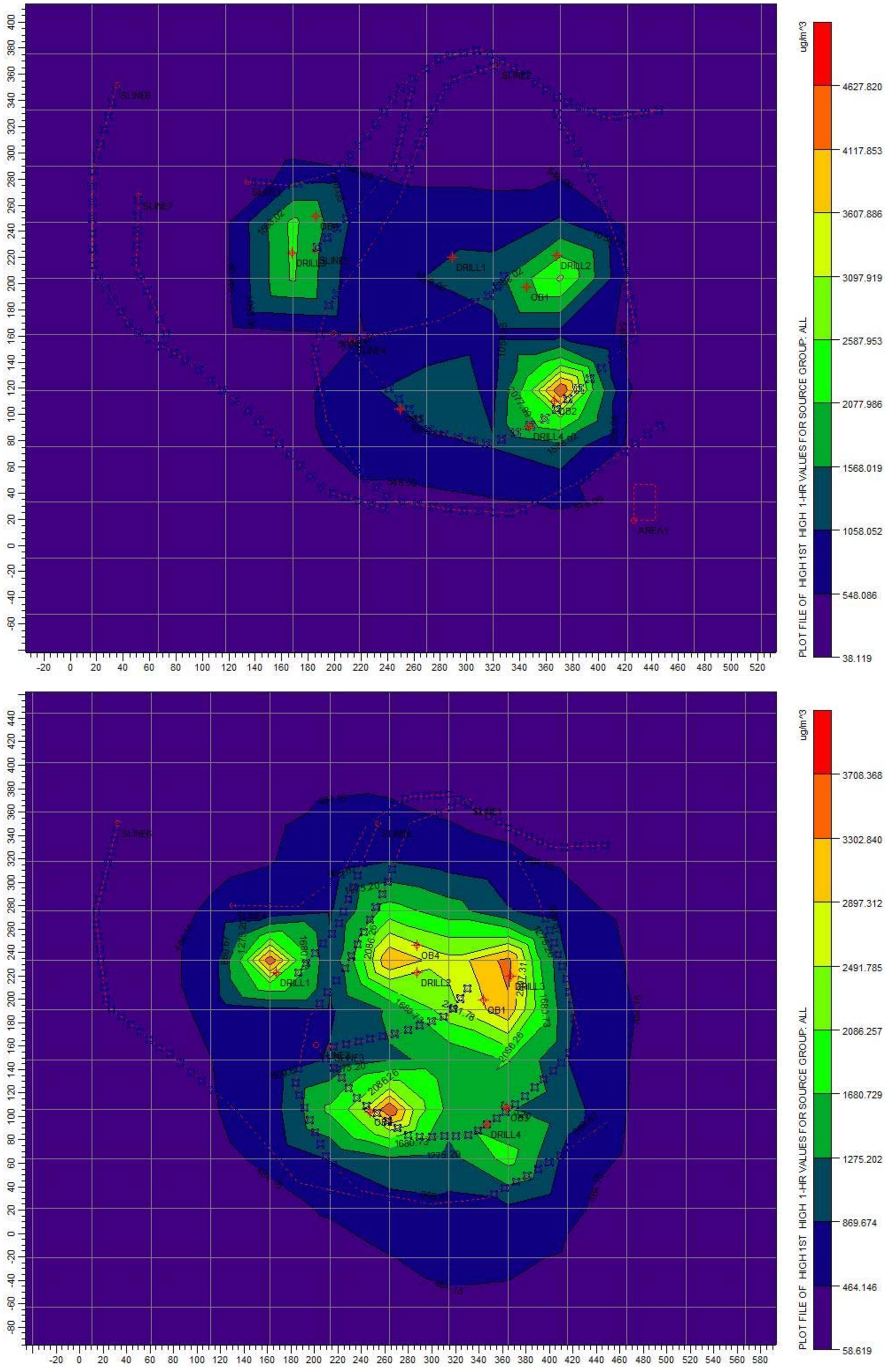

Fig. 5. Predicted concentration of PM_{10} in Rajapur OCP in winter (upper) and summer (lower)

The GM values were found to be 1.04, 1.08 and 1.05 for the three mines, respectively. Thus both NMSE and GM values indicated fairly good prediction. All the five observations (FAC2) were lying within the factor of the two further emphasizing accuracy of prediction. The *d* value was 0.93, 0.92 and 0.93 for the three mines, respectively, conveying 93%, 92% and 93% model accuracy for winter PM_{10} concentration.

The calculated *FB* values during summer were found to be –0.08, –0.04 and 0.048 for the three mines, respectively, which depicted slightly underestimates of the PM_{10} concentrations for the Katrasgarh and Muraidih, whereas slight overprediction occurred for the Rajapur OCP. Note that *x* and *y* axes denote locations of mining activities (i.e., latitude and longitude) whereas color coding represents PM_{10} concentration profile. The calculated NMSE values were found to be 0.007, 0.001 and 0.002 for the three mines, respectively, and are nearly perfect for prediction.

Similarly, the *GM* values were 0.92, 1.00 and 1.05 for the three mines, respectively, thereby emphasizing good prediction. All the five observations (FAC2) were lying within factor of two, further emphasizing the accuracy of prediction. The *d* values were 0.93, 0.84 and 0.81 for the three mines, respectively, conveying 93%, 84% and 81% model accuracy for the summer PM_{10} concentration.

4.5. INDEX OF AGREEMENT BETWEEN AERMOD EVALUATED PM_{10} AND MONITORED CONCENTRATIONS

Evaluated PM_{10} concentrations were compared with the monitored field concentrations as shown in Figs. 6–8. Five observed concentrations at five different location points were taken into consideration in the present study.

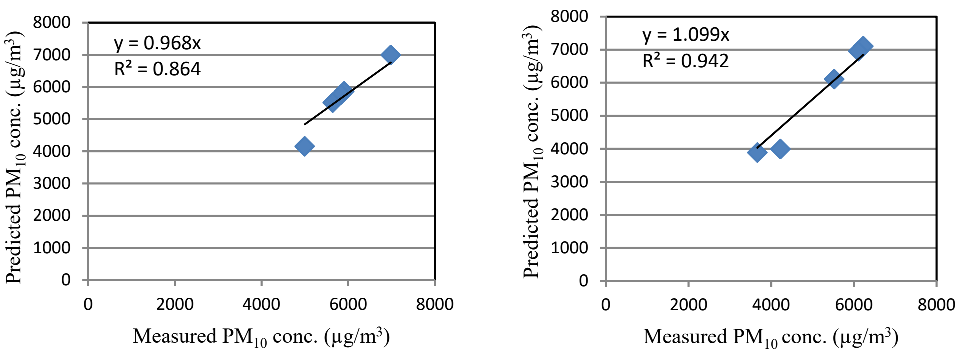

Fig. 6. Predicted versus measured PM_{10} concentration of Katrasgarh OCP in winter (left) and summer (right)

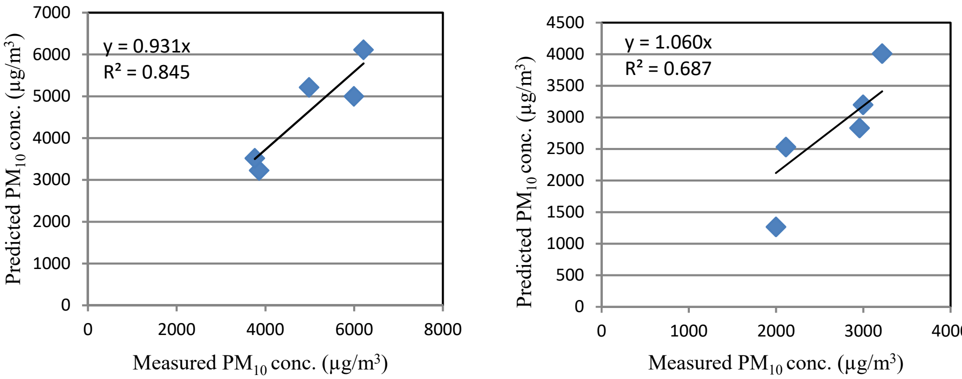

Fig. 7. Predicted versus measured PM_{10} concentration of Muraidih OCP in winter (left) and summer (right)

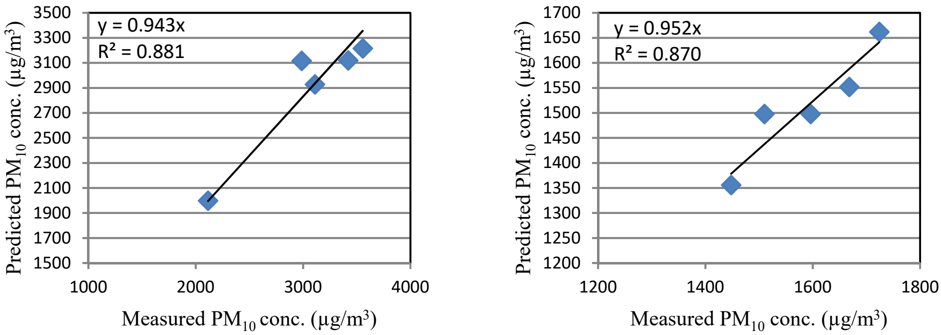

Fig. 8. Predicted versus measured PM_{10} concentration of Rajapur OCP in winter (left) and summer (right)

The index of agreement is 0.86, 0.84 and 0.88 for the three mines, respectively, reaching 86%, 84% and 88% model accuracy for winter background PM_{10} concentration. Similarly, the index of agreement is 0.94, 0.68 and 0.87 for the three mines, respectively, reaching 94%, 68% and 87% model accuracy for summer background PM_{10} concentration. In order to assess the effectiveness of model output as mentioned above, widely used U.S. EPA AP-42 emission factors for identical opencast mining activities were now considered and used in the model.

4.6. AERMOD EVALUATED PM_{10} CONCENTRATION USING U.S. EPA AP-42 EMISSION FACTORS

The predicted PM_{10} concentrations (from isopleths) were then compared with the measured concentrations (Figs. 9–11). The indices of agreement were observed to be

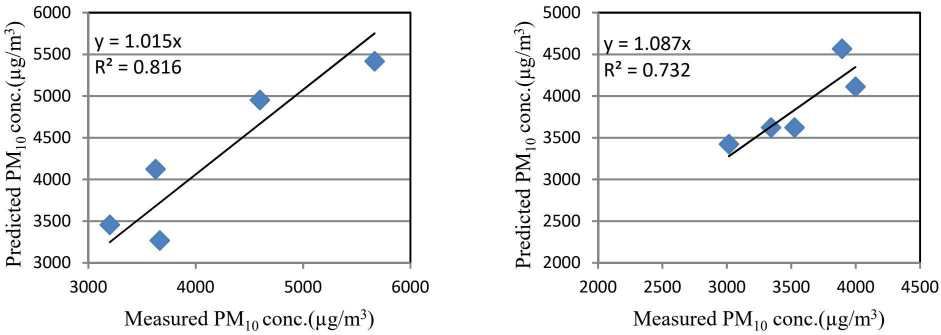

Fig. 9. AP-42 based predicted versus measured PM_{10} concentration of Katrasgarh OCP in winter (left) and summer (right)

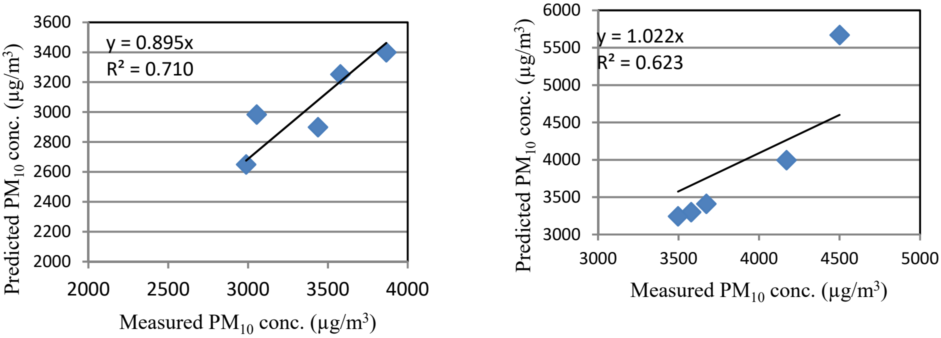

Fig. 10. AP-42 based predicted versus measured PM_{10} concentration of Muraidih OCP in winter (left) and summer (right)

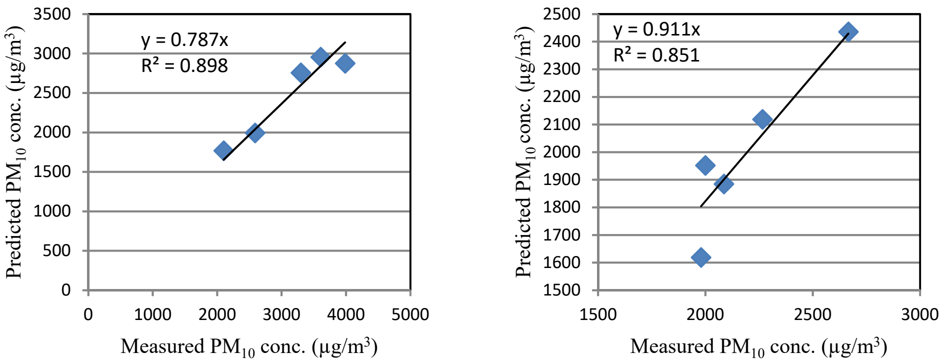

Fig. 11. AP-42 based predicted versus measured PM_{10} concentration of Rajapur OCP in winter (left) and summer (right)

0.81, 0.71 and 0.89 for the three mines, respectively, indicating 81%, 71% and 89% model accuracy for winter PM_{10} concentrations, respectively. On the other hand, the indices of agreement were 0.73, 0.62 and 0.85 for the three mines, respectively depicting 73%, 62% and 85% model accuracy for summer PM_{10} concentrations.

5. CONCLUSIONS

The opencast coal mining operations have been attaining importance in recent years to meet the ever increasing production targets, thereby elevating the issue of particulate pollution. The use of various models like AERMOD serves the purpose of evaluating/predicting the concentration profiles of particulate matter in and around coal mining complex. In the present study, overall PM_{10} concentration profiles (in the form of isopleths) were evaluated based on evaluated emission rates of commonly occurring opencast coal mining activities (not shown in this paper) for both winter and summer seasons. These isopleths diagrams display the overall PM_{10} profiles within the active mining areas of concerned opencast mines.

While comparing these predicted values with monitored values of PM_{10}, evaluated indices of agreement were found 0.86, 0.84 and 0.88 during winter background and 0.94, 0.68 and 0.87 during summer background for the three opencast mines, respectively. Similarly, performance evaluation of AERMOD predicted concentrations over actual field concentrations using a set of five statistical tools, revealed more or less fairly good prediction for both the seasons.

In a similar manner, U.S. EPA AP-42 based emission factor data for identical mining activities with same meteorological database, were used for AERMOD was run for the evaluation of PM_{10} profiles. Correlation analysis indicated 71–89% and 62–85% model accuracy for winter and summer, respectively for these three selected mines.

In spite of marked improvement in recent years, a perceptible and predictive understanding of the sources of particulate matter in mining areas are still confined, and therefore pose a considerable research challenge. Predictive approach is cost effective and hassle free, at the same time facilitates the formulation of appropriate mitigation strategy and air environmental management.

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