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# Spatial and temporal variations of SPM, RPM, $SO_2$ and $NO_x$ concentrations in an opencast coal mining area†

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A study for assessment and management of air quality was carried out in the Ib Valley area of the Ib Valley coalfield in Orissa state, India. The 24 h average concentrations of suspended particulate matter (SPM), respirable particulate matter (RPM), sulfur dioxide ($SO_2$) and oxides of nitrogen ($NO_x$) were determined at regular intervals throughout one year at twelve monitoring stations in residential areas and six monitoring stations in mining/industrial areas. The 24 h average SPM and RPM concentrations were 124.6–390.3 μg $m^{-3}$ and 25.9–119.9 μg $m^{-3}$ in residential areas, and were 146.3–845.2 μg $m^{-3}$ and 45.5–290.5 μg $m^{-3}$ in industrial areas. During the study period, 24 h and annual average SPM and RPM concentrations exceeded the respective standards set in the Indian national ambient air quality standard (NAAQS) protocol as well as USEPA, EU, WHO and World Bank standards at most of the residential and industrial areas. However, concentrations of $SO_2$ (annual average: 24.6–36.1 μg $m^{-3}$ and 24 h average: 17.0–46.3 μg $m^{-3}$) and $NO_x$ (annual average: 23.6–40.9 μg $m^{-3}$ and 24 h average: 18.3–53.6 μg $m^{-3}$) were well within the prescribed limit of the NAAQS and international standards in both residential and industrial areas. The temporal variations of SPM and RPM fitted polynomial trends well and on average in the mining area 31.91% of the SPM was RPM. The linear regression correlation coefficients between SPM and RPM and between $NO_x$ and $SO_2$ were 0.94 ($\pm$0.04) and 0.66 ($\pm$0.10), respectively. The optimum interpolation technique, kriging, determined that maximal concentrations of SPM and RPM occurred within the mining site. Highest concentrations of particulate matter were observed during the winter season followed by summer, autumn and rainy seasons. An action plan is formulated for effective control of air pollution at source, and mitigative measures should include implementation of green belts around the sensitive areas where the concentration of air pollutants exceeds the standard limit.

## Introduction

Coal mining is one of the core industries in India and plays a positive role in the economic development of the country.[1,2] Its environmental impact cannot be ignored but, to some extent, is unavoidable.[3–7] Most major mining activities contribute directly or indirectly to air pollution.[8,9] Sources of air pollution in the coal mining areas generally include drilling, blasting, overburden loading and unloading, coal loading and unloading, road transport and losses from exposed overburden dumps, coal handling plants, exposed pit faces and workshops.[9] These air pollutants reduce air quality and this ultimately affects people, flora and fauna in and around mining areas.[10–13] The major air pollutants produced by opencast mining are suspended particulate matter and respirable particulate matter,[9,14] which is in contrast to vehicular emissions where lead and gaseous pollutants are the major concern.[15,16]

The environmental impact of coal mining areas must be assessed by detailed studies of air quality.[17–21] Analysis of temporal and spatial variation of air pollutant concentration is also essential[22,23] and, where necessary, effective mitigative measures including green belts can be devised for sensitive areas.[24–26]

The air quality was studied in the Ib Valley area of the Ib Valley coalfield, a coal mining region surrounded by villages. The conditions are similar to those of all the new and proposed Indian opencast coal mines. The study sought to determine the severity of the level of air pollutants in the mining area relative to the Indian National Ambient Air Quality Standard (NAAQS) protocol[27] and the extent of temporal and spatial variation of particulate matter over a one-year period. A specific objective was to assess the spatial distribution of particulate matter over the Ib Valley area by the use of a spatial prediction technique, kriging,[22,23] and formulate an action plan for controlling air pollution in the area based on the impact assessment study. Respirable particulate matter (RPM) being the main focus of concern for human health, this study aimed to help in benchmarking the RPM concentration by determining the concentration of suspended particulate matter (SPM) for a similar mining site.

## Materials and methods

### Study site

The Ib Valley area is located in the Ib Valley coalfield situated in parts of Jharsuguda, Sambalpur and Sundergarh districts of Orissa state and is operationally under the control of Mahanadi Coalfields Limited, Sambalpur, India (Fig. 1). The Ib River is a tributary of the Mahanadi River. The coalfield has large reserves of coal suitable for power generation and extends over an area of 1375 $km^2$, the strike line swinging from north-south to east-west in the southern and northern

† Electronic supplementary information (ESI) available: Five figures showing polynomial regression analyses of monthly averages of RPM concentrations for the residential and industrial areas during a one year period, spatial distribution of seasonal RPM concentrations over the study area for winter, summer, autumn and rainy seasons, and variations of $SO_2$ and NOx concentrations in the study area with annual average, and 24 h average maximum, minimum and 95th percentile values. See http://www.rsc.org/suppdata/em/b3/b309372g/

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**Fig. 1** Location of the study site and sampling stations.

extremes. The geology of the area is mainly of the Lower Gondwana system.[28]

The Ib Valley area is surrounded by various industries, *viz.* Tata Refractories, Orient Paper Mills, Orient underground mining area, Thermal Power Station and the Lakhanpur area. The area consists of three opencast projects (OCP), namely Samleswari (S.O.C.P.), Lilari (Lilari O.C.P.) and Lajkura (L.O.C.P.) (Fig. 1), which produced 3.836, 0.941 and 0.752 Mt per year, respectively during 1998–1999.

The climate of the area is dry tropical, and there are four seasons, namely summer (February–May), rainy (June–August), autumn (September–October) and winter (November–January). Meteorological data for a period of 27 years (1973–1999) were collected from the Jharsuguda Meteorological Station of the Indian Meteorological Department (IMD) located within the study area (Fig. 1). During the summer months the temperature can reach 47 °C and in winter months can fall to 10 °C. Annual mean maximum and minimum temperatures are 33.2 °C and 20.5 °C, respectively. Wind speed in the area varies from 8.2–16.0 km $h^{-1}$ with an average of 11.8 km $h^{-1}$. The annual calm period (wind speed $<$2.1 km $h^{-1}$) for the area is 50% and 40% of total duration at 08:30 and 17:30 hours, respectively. The predominant wind direction for the area is towards the south-west. Atmospheric stability classes (Pasquill-Gifford) were computed using the Turner classification scheme[29–31] and it varied from 1 to 6 during midday and night, respectively. The south-west monsoon is the principal source of rainfall in the area, the average rainfall at the Jharsuguda IMD station being 1400 mm per year and there being on average 81 rainy days per year.

## Methodology

Monitoring stations were placed to evaluate air quality and plan any control measures. The 24 h average sampling and analysis were done twice in a week for residential areas (buffer zone) and six times monthly for industrial areas (core zone/mining area) during the year from September 1998 to August 1999. The siting of eighteen air sampling stations (twelve in the buffer zone and six in the core zone, Fig. 1) was based on prevailing micro-meteorological conditions and availability of infrastructure. Details of sampling stations along with the respective sources of air pollution and activities during sampling are given in Table 1. Concentrations of carbon monoxide (CO) and lead (Pb) were below detectable limits or negligible as per the bi-monthly monitoring report[32] for the area during September 1997 to August 1998 and because of this CO and Pb concentrations were not measured in the present study. Suspended particulate matter (SPM) including $PM_{10}$ (particulate matter $<$10 μm aerodynamic diameter) or

**Table 1** Total number of 24 h average samples, percentage of sample recovery, percentage of recovered samples exceeded the standard limit of SPM and RPM, and sources of air pollution

| Station code | Location | Total number of samples | Percentage of sample recovery | Percentage of recovered samples exceeded the standard: SPM | Percentage of recovered samples exceeded the standard: RPM | Sources of air pollution[a] |
|---|---|---|---|---|---|---|
| *Residential area (buffer zone)* | | | | | | |
| A1 | Gopi vihar colony | 104 | 93 | 54 | 0 | 1, 2, 4 |
| A2 | Kudopali village | 104 | 94 | 91 | 25 | 1, 2, 4 |
| A3 | Orampara village | 104 | 90 | 58 | 0 | 1, 2, 4 |
| A4 | Samleswari colony | 104 | 94 | 58 | 0 | 1, 2 |
| A5 | Lajkura village | 104 | 91 | 75 | 29 | 1, 2, 4 |
| A6 | Madhuban nagar, rehabilitation site of Lajkura OCP | 104 | 92 | 75 | 13 | 1 |
| A7 | Lajkura VIP guest house | 104 | 93 | 83 | 29 | 1, 2 |
| A8 | Brajraj nagar market | 104 | 89 | 100 | 29 | 2, 4 |
| A9 | GM complex of Ib Valley area | 104 | 93 | 71 | 25 | 2 |
| A14 | Khairkuni village | 104 | 91 | 58 | 0 | 1, 2, 4 |
| A15 | TRL village | 104 | 94 | 54 | 0 | 1, 2 |
| A16 | Pipalmal village | 104 | 93 | 50 | 0 | 1, 2, 4 |
| *Industrial area (core zone)* | | | | | | |
| A10 | Railway siding of Samleswari OCP | 72 | 90 | 75 | 76 | 1, 2, 3 |
| A11 | Project office of Samleswari OCP | 72 | 93 | 6 | 22 | 1, 2, 3 |
| A12 | CHP of Lajkura OCP | 72 | 91 | 75 | 86 | 1, 2, 3 |
| A13 | Project office of Lajkura OCP | 72 | 92 | 6 | 33 | 1, 2, 3, 4 |
| A17 | CHP of Lilari OCP | 72 | 91 | 75 | 85 | 1, 2, 3 |
| A18 | Project office of Lilari OCP | 72 | 94 | 63 | 67 | 1, 2, 3, 4 |

[a] 1 - Area sources (fire area/exposed dump/exposed pit surface/stockyard/coal handling plant/workshop/railway siding/domestic coal burning, *etc.*); 2 - Line source (transport road/haul road/unpaved road, *etc.*); 3 - Point sources (drilling/blasting/loading/unloading, *etc.*) and 4 - Other sources (other industry/commercial and domestic activities, *etc.*).

respirable particulate matter (RPM), sulfur dioxide ($SO_2$) and oxides of nitrogen ($NO_x$) were sampled by high volume samplers (HVS; Model APM 460 of Envirotech Instrument Pvt. Ltd., New Delhi) with an average flow rate $>1.1$ m$^3$ min$^{-1}$ and having gaseous sample collection attachments.

The HVS having RPM and gaseous attachments were kept on the single storied houses' roof-top, approximately 3 m ($\pm$0.3 m) height above ground, at all the monitoring stations. The height of sampling for a particular monitoring station was the same throughout the study period. The exhaust gas was used after having passed the SPM/RPM chamber for collection of gaseous samples. The HVS were regularly calibrated for the proper measurement of air pollutants. Samples were collected at regular intervals, and a minimum of eight samples for a residential area and six samples for an industrial area were collected within a month. During the study period there were no significant changes in the climate within a month, and mining, allied activities and sources of air pollution were almost uniform in the area. Therefore, the number of samples was representative of a complete month both for residential and industrial areas. All the samples were not accepted and when errors were observed, samplings were repeated for collection of representative samples for the respective monitoring station. The following criteria were applied to reject the eventually dubious samples collected from any sampling station: (1) results of sample analysis were quite different from the trend of a particular air pollutant for the monitoring station without any significant change in the nearby pollution generating sources in the field; (2) occurrence of sudden significant uncommon air polluting sources near the sampling station (*e.g.* burning of grass, coal, wood, tar-coal *etc.*) which generally occurred 2–3 times during the study period especially at a few monitoring stations located in the residential area, (3) power failure for longer duration (more than 3 h) during the collection of 24 h average sample; (4) occurrence of sudden extreme weather conditions (*e.g.* heavy rainfall, cyclone *etc.*) which occurred twice during the study period; and (5) errors in sampling and analysis method. Among all these situations only a few situations occurred at the respective monitoring station and the percentage of sample recovery ranged from 89 to 94% (Table 1). The recovered samples were considered as actual total measurements for analysis and impact assessment of air quality.

The 24 h average samples were obtained following the NAAQS protocol of the Central Pollution Control Board, New Delhi.[27] SPM and RPM were measured by difference in weight using electronic balance of Mettler, Switzerland; $SO_2$ by the improved West and Gaeke method with ultra-violet fluorescence, and $NO_x$ by the Jacob-Hochheiser modified method (Na-Arsenic) with gas phase chemiluminescence using Spectronic 20D of Milton Roy, UK.[27,33] The 24 h average data measured for all the monitoring stations during one year were statistically analysed following Ott[34] and annual averages of the air pollutants were calculated for each station. The 24 h and annual average concentrations of air pollutants were compared with the NAAQS protocol to determine air quality status. The monitoring stations were grouped into six categories by comparing the percentage of SPM or RPM concentration with the respective standard limit for each particular area. The categories of SPM or RPM concentration with respect to the relevant standard limit were: *very good* (0–50%), *good* ($>$50–75%), *fair* ($>$75–100%), *poor* ($>$100–125%), *very poor* ($>$125–150%) and *dangerous* ($>$150%).

The temporal and spatial variation in particulate matter was analysed to establish the seasonal trend by using polynomial regression analysis to obtain the best fit.[23,35–42] Kriging, the optimum interpolation technique was used to obtain the spatial distribution of particulate matter over the one-year period, the idea behind kriging being to make inferences from unobserved values of a random process from data observed at known spatial locations.[23] A detailed explanation of the kriging method is available in the literature.[43–45] Linear regression analysis was carried out to derive the best fit equation between measured SPM and RPM concentrations and the correlation coefficient.[23]

## Results

### SPM concentration

**Residential areas.** Annual average, and 24 h average maximum, minimum and 95th percentile values of SPM

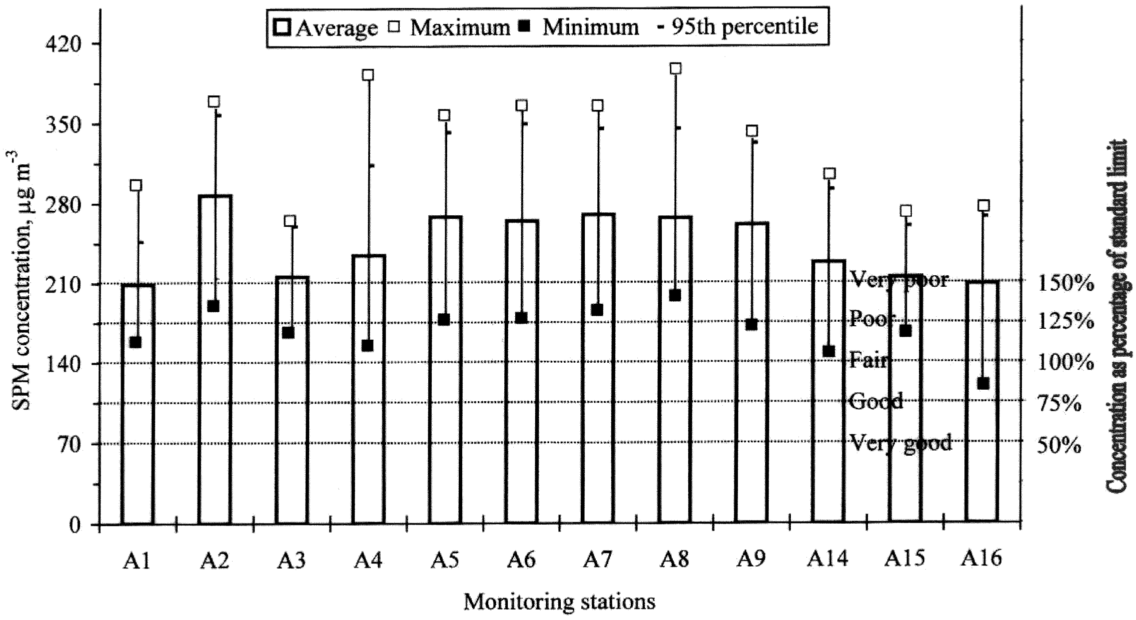


**Fig. 2** Variation of SPM concentrations in the residential area with annual average, 24 h average maximum, minimum and 95th percentile values, and comparison with the threshold value.

concentrations measured at twelve monitoring stations during the one year period in the residential areas are illustrated in Fig. 2. The results were compared with the NAAQS protocol (Table 2) for the residential area. It was observed that the annual average SPM concentration at all the monitoring stations was much higher than the standard limit of 140 µg $m^{-3}$ for a residential area. The annual average SPM concentration at the A1 and A16 monitoring stations did not quite reach the 'very poor' category. However, all other monitoring stations came in the 'dangerous' category. The range of annual average SPM concentration was between 208.9 µg $m^{-3}$ and 287.5 µg $m^{-3}$ at all monitoring stations. The 24 h average SPM concentration was found to vary between 124.6 µg $m^{-3}$ (A16 station) and 390.3 µg $m^{-3}$ (A8 station). The percentage of actual measurements of the 24 h average SPM concentration that exceeded the standard limit varied from 50% (A16 station) to 100% (A8 station) (Table 1).

**Industrial area.** Among all six monitoring stations in the industrial/mining area, the highest annual average SPM concentration of 605 µg $m^{-3}$ was observed at A17, the coal handling plant (CHP) of Lilari opencast project (OCP) and the lowest of 386.3 µg $m^{-3}$ was measured at A11, the Samleswari project office (Fig. 3). Annual average SPM concentration was higher than the threshold limit of 360 µg $m^{-3}$ at all the monitoring stations. The A11 and A13 stations came in the 'poor' category, the A18 station in the 'very poor' category and the other three monitoring stations (A10, A12 and A17) in the 'dangerous' category. The 24 h average SPM concentration ranged from 146.3 µg $m^{-3}$ (A11 station) to 845.2 µg $m^{-3}$ (A17 station). The 24 h average readings exceeded the standard limit at all the monitoring stations during the study period and it varied between 6% (A11 and A13 stations) and 75% (A12 and A17 stations) of the total measurements (Table 1).

## RPM concentration

**Residential area.** The annual average RPM concentration was more than the threshold limit of 60 µg $m^{-3}$ at all the monitoring stations (Fig. 4) and the A1, A3, A4, A14, A15 and A16 monitoring stations came in the 'poor' category and all other monitoring stations in the 'very poor' category. The annual average RPM concentration varied between 66.2 µg $m^{-3}$ (A1 station) and 88.2 µg $m^{-3}$ (A5 station). The 24 h average SPM concentration ranged from 25.9 µg $m^{-3}$ (A5 station) to 119.9 µg $m^{-3}$ (A6 station). The 24 h average readings never exceeded the standard limit of 100 µg $m^{-3}$ at the A1, A3, A4,

**Table 2** National ambient air quality standards 1994 for sulfur dioxide, oxides of nitrogen, and respirable and suspended particulate matter,[27] and international standards

| | | Concentration in ambient air/µg $m^{-3}$ | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Indian standard | | | International standards | | | |
| Pollutant | Time weighted average | Industrial area | Residential, rural and other areas | Sensitive area | USEPA | EU | WHO | World Bank[c] |
| $SO_2$ | Annual average[a] | 80 | 60 | 15 | 80 | 80 | 40–60 | 50 |
| | 24 h[b] | 120 | 80 | 30 | 365 | 250 | 100–150 | 150 |
| $NO_x$ | Annual average[a] | 80 | 60 | 15 | 100 | 200 | — | — |
| | 24 h[b] | 120 | 80 | 30 | — | — | 150 | — |
| SPM | Annual average[a] | 360 | 140 | 70 | 75 | 150 | 60–90 | 80 |
| | 24 h[b] | 500 | 200 | 100 | 260 | 300 | 150–230 | 230 |
| RPM | Annual average[a] | 120 | 60 | 50 | 50 | 40 | 50 | 50 |
| | 24 h[b] | 150 | 100 | 75 | 150 | 50 | — | 150 |

[a] Annual arithmetic mean of 104 measurements in a year, twice a week, 24 hourly at uniform interval; [b] 24 hourly values should be met 98% of the time in a year, however, 2% of the time it may exceed but not on two consecutive days; [c] Moderate airshed.

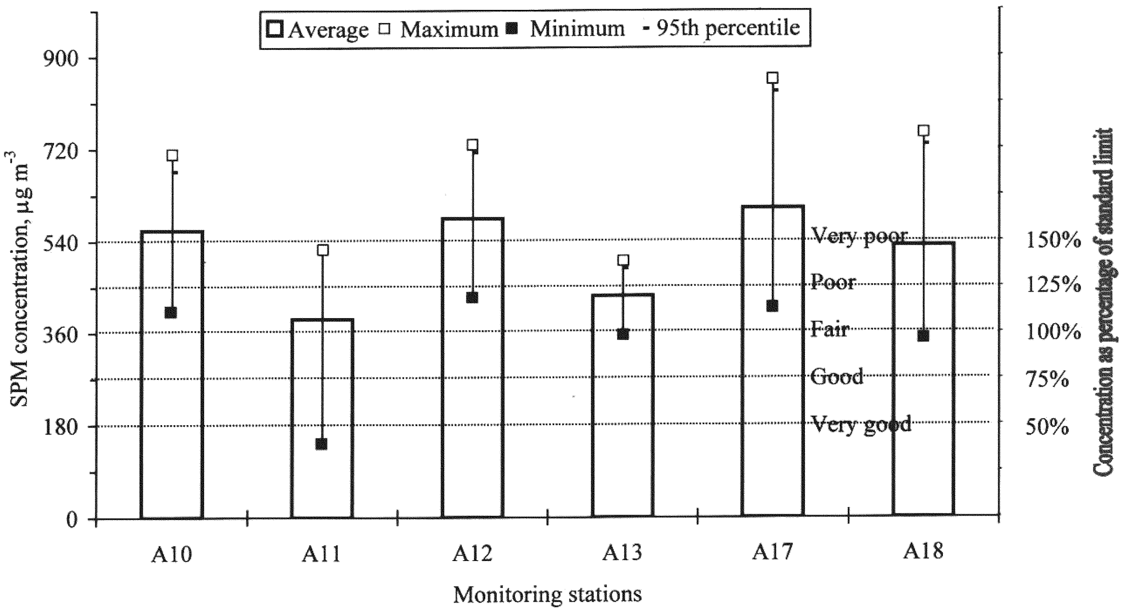


**Fig. 3** Variation of SPM concentrations in the industrial area with annual average, 24 h average maximum, minimum and 95th percentile values, and comparison with threshold value.

A14, A15 and A16 monitoring stations during the study period, however, they did elsewhere, 13% (A6 station) to 29% (A5, A7 and A8 stations) of the total measurements exceeding the threshold limit (Table 1).

**Industrial area.** Of the six monitoring stations in the industrial area, only at the A11 monitoring station was the annual average RPM concentration within the prescribed limit of 120 µg m$^{-3}$ (Fig. 5) which came in the 'fair' category. The A13 monitoring station came in the 'poor' category, A10 and A18 in the 'very poor' category, and A12 and A17 in the 'dangerous' category. The annual average RPM concentration varied between 119.2 µg m$^{-3}$ (A11 station) and 191.5 µg m$^{-3}$ (A17 station). The 24 h average RPM concentration ranged from 45.5 µg m$^{-3}$ (A11 station) to 290.5 µg m$^{-3}$ (A12 station). The percentage of total readings exceeding the 24 h average threshold limit of 150 µg m$^{-3}$ which ranged from 22% (A11 station) to 86% (A12 station) of the total measurements (Table 1).

### Spatio-temporal variation of SPM and RPM

The temporal variations of SPM and RPM fitted polynomial trends (average correlation coefficient $R^2$ of 0.82 $\pm$ 0.08 for SPM; Fig. 6a and 0.81 $\pm$ 0.08 for RPM in the residential area, and 0.86 $\pm$ 0.08 for SPM; Fig. 6b and 0.84 $\pm$ 0.07 for RPM in the industrial area). The correlation coefficient between SPM and RPM was 0.94 ($\pm$0.04). On average, the RPM in the

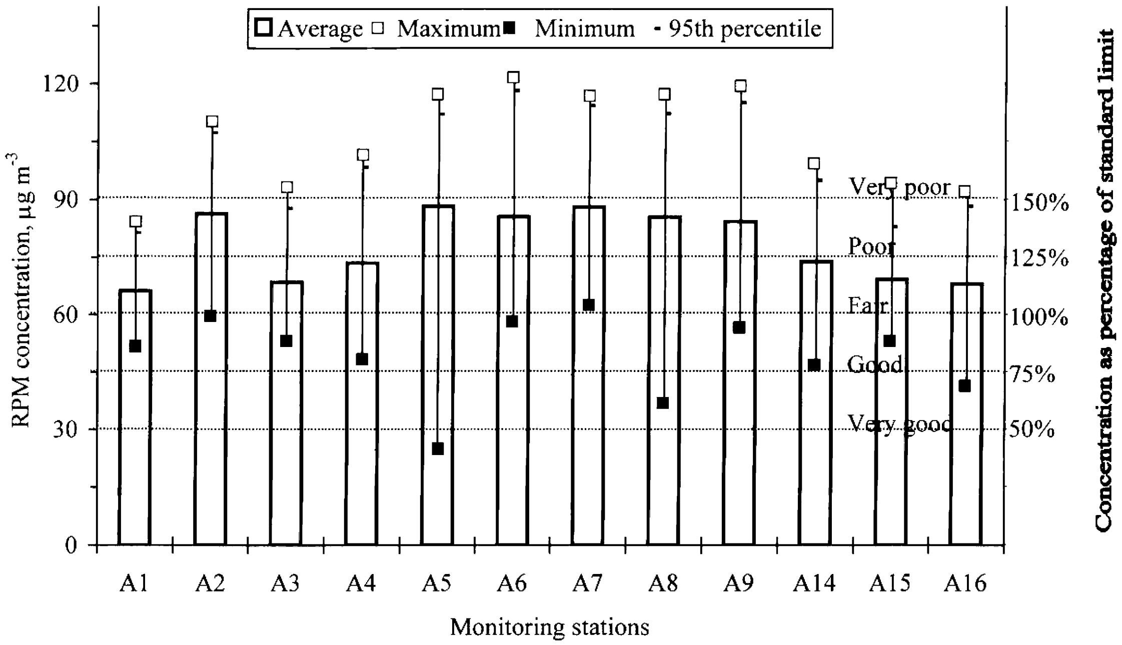


**Fig. 4** Variation of RPM concentrations in the residential area with annual average, 24 h average maximum, minimum and 95th percentile values, and comparison with threshold value.

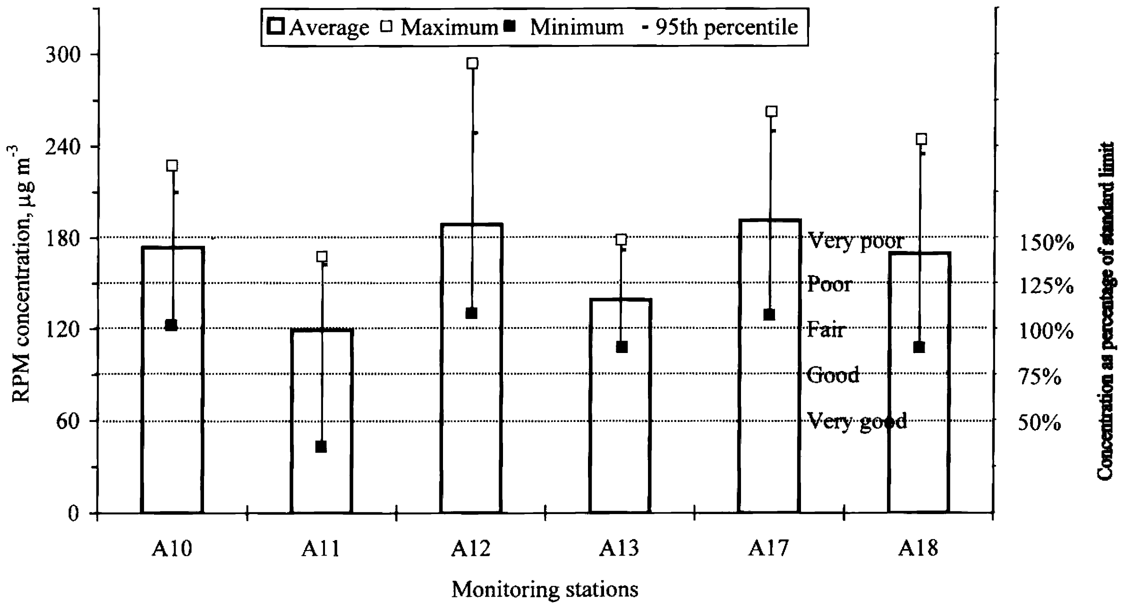


**Fig. 5** Variation of RPM concentrations in the industrial area with annual average, 24 h average maximum, minimum and 95th percentile values, and comparison with threshold value.

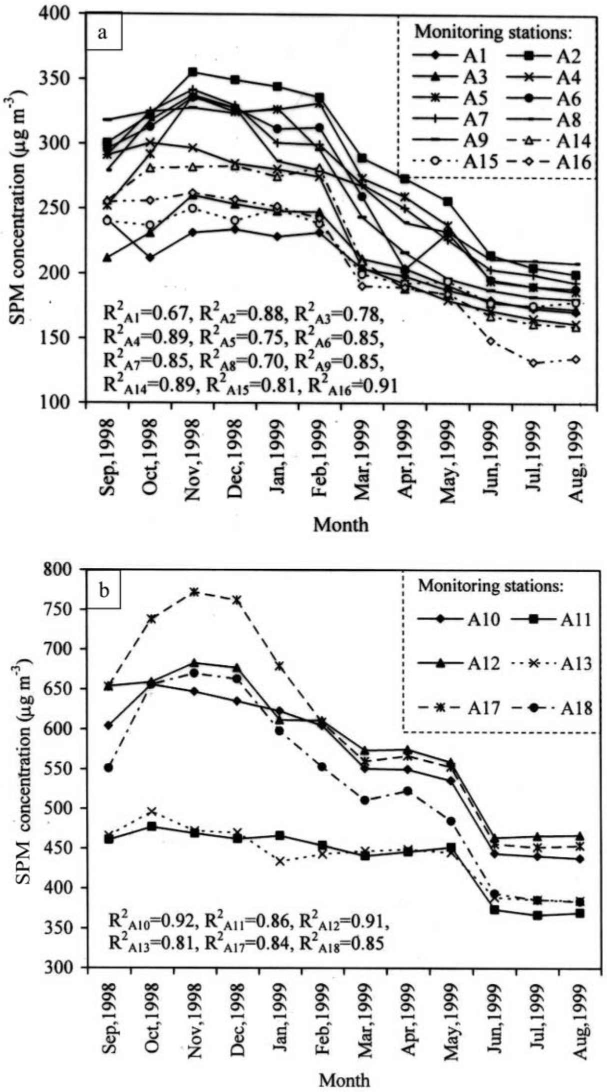


**Fig. 6** Polynomial regression analysis of monthly average of SPM concentration for the monitoring stations during a one year period for (a) residential and (b) industrial areas.

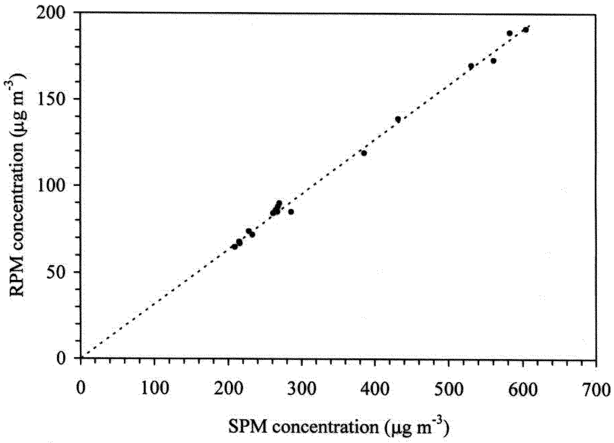


**Fig. 7** Linear regression analysis of annual average of SPM and RPM concentrations for all the monitoring stations.

ambient air of the mining area constituted 31.91% (±1.08%) of the SPM, the best fit equation being $y = 0.3174x - 0.1253$ (correlation coefficient of 0.99; Fig. 7). Linear regression analysis was also performed between concentrations of $NO_x$ and $SO_2$, and the correlation coefficient of $NO_x$ with $SO_2$ was 0.66 (±0.10). Transportation of coal was the main source of SPM generation and other sources of air pollutants are given in Table 1. The kriging technique determined that maximal concentrations of SPM (Fig. 8) and RPM occurred within the mining site. The concentrations gradually diminished with increasing distance from the mining site. Maximal concentration of particulate matters was observed during the winter season followed by summer, autumn and rainy seasons (Fig. 8).

## $SO_2$ and $NO_x$ concentrations

The mean annual average $SO_2$ concentration among all the monitoring stations ranged between 24.6 µg m$^{-3}$ (A4 station) and 36.1 µg m$^{-3}$ (A15 station), being well below the threshold limits of 60 µg m$^{-3}$ (residential) and 80 µg m$^{-3}$ (industrial). The 24 h average $SO_2$ concentrations were between 17.0 µg m$^{-3}$ (A4 station) and 46.3 µg m$^{-3}$ (A9 station), well within the standard limits of 80 µg m$^{-3}$ (residential) and 120 µg m$^{-3}$ (industrial).

The $SO_2$ in the residential areas came from open burning of raw coal and other domestic and commercial activities. The annual and 24 h average $NO_x$ concentrations were found to be well within the prescribed limit at all the monitoring stations, the range of annual average $NO_x$ concentrations lying between 23.6 μg $m^{-3}$ (A4 station) and 40.9 μg $m^{-3}$ (A3 station). The 24 h average $NO_x$ concentrations varied from 18.3 μg $m^{-3}$ (A4 station) to 53.6 μg $m^{-3}$ (A9 station).

## Discussion

The concentration of particulate matter at most of the monitoring stations reached a maximum during winter and was at its minimum in the rainy season; this is similar to the reports by various researchers[13,32,46,47] for Indian coal mining areas, and Karaca[48] and Tayanc[23] for Istanbul in Turkey. However, for certain urban areas maximal concentrations of particulate matter are observed in the summer season.[11,15,16,21] The average monthly production rate was almost uniform throughout the study period. Therefore, the reason for temporal or seasonal variations was only related to the meteorological parameters. In winter, anti-cyclonic conditions prevailed, which was characterised by calm or light winds and restricted mixing depth due to a stable or inversion atmospheric lapse rate, resulting in little dispersion or dilution of pollutants, which, in its turn, helped in the build-up of pollution concentrations to the higher levels. The Monsoon experienced the lowest SPM and RPM levels because of the wash-out of airborne particulates and other gaseous pollutants by intermittent precipitation. It was also observed that in general the SPM and RPM levels tended to decrease with increasing relative humidity.

Concentrations of particulate matter at monitoring stations A6 and A7 were inversely related to the temporal trend of other monitoring stations during certain periods as a result of a change in the domestic activities near these monitoring stations at the time. The strong correlation between SPM and RPM indicates that the concentration of RPM, which is the main concern for human health affects,[6,12] would be useful for benchmarking the RPM concentration without field measurement for any opencast coal mining area with similar conditions, by knowing the SPM concentration. Coal transportation was the main source of SPM generation as reported by various researchers.[46,47,49,50–52] Based on the dust samples' analysis of the mining area by a differential thermal analyser, it was reported that an average of 78% (±6%) of dust was of coal origin.[32] This indicates that major share of dust pollution in the study area was from mining and allied activities. Maximal concentrations of SPM and RPM found in the mining area and levels gradually diminished with increasing distance due to transportation, deposition and dispersion of particles as analysed by different researchers.[29,53–55] The dispersion of particulate matter tended to be towards the south-west, which followed the annual predominant wind direction of the area.[4,6,19]

The annual and 24 h average SPM and RPM concentrations were compared with the national ambient air quality standards (health related) of United Sates Environmental Protection Agency (USEPA).[56] The annual and 24 h average SPM concentrations were higher than the prescribed limit of 75 μg $m^{-3}$ and 260 μg $m^{-3}$, respectively at all the monitoring stations. Similarly, annual average RPM concentrations were also higher than the threshold limit of 50 μg $m^{-3}$ at all the monitoring stations. However, 24 h average RPM concentrations were below the standard limit of 150 μg $m^{-3}$ at all the monitoring stations in the residential area and it was higher at

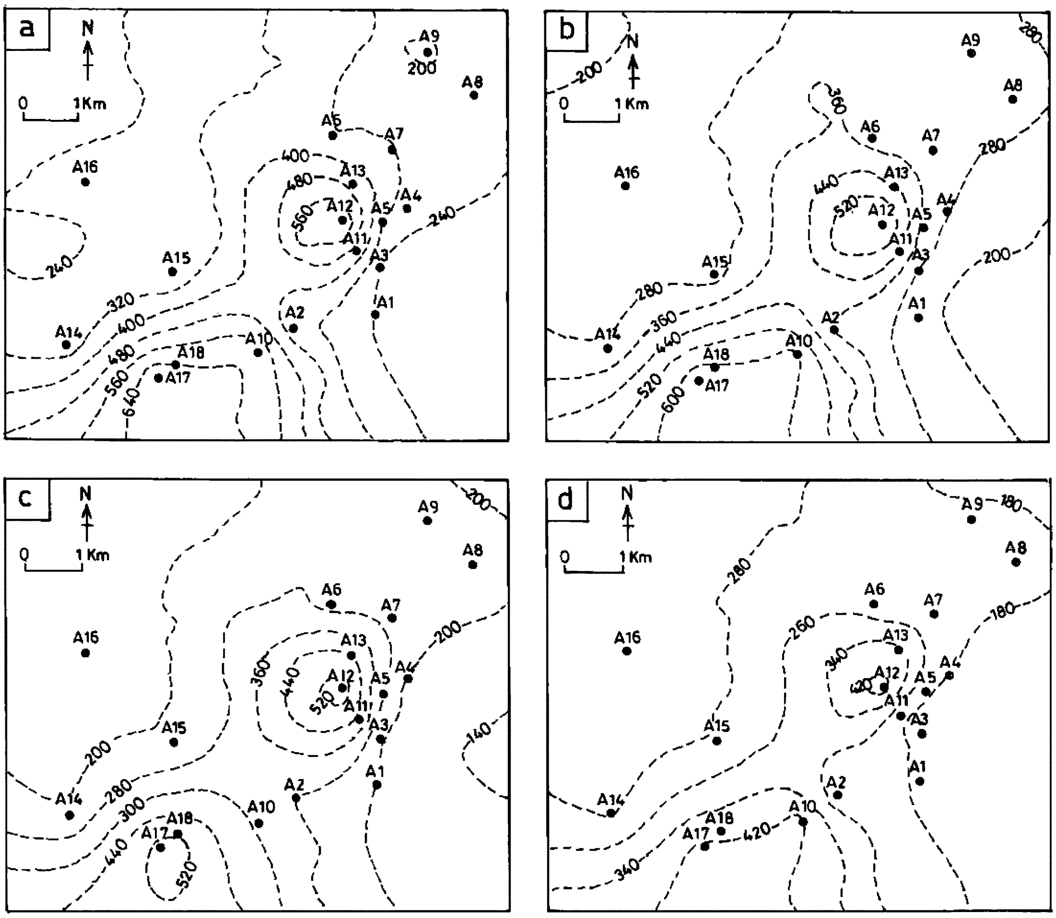

Fig. 8 Spatial distribution of seasonal SPM concentration in μg $m^{-3}$ over the study area for (a) winter, (b) summer, (c) autumn and (d) rainy seasons.

all the monitoring stations in the industrial/mining area. Annual and 24 h average concentrations of $SO_2$ and $NO_x$ were well within the standard limit at all the monitoring stations. Concentrations of $NO_x$ at few residential places were higher than the values in the industrial areas, because of domestic and commercial activities in the respective residential areas. In general, the 24 h and annual average SPM and RPM concentrations were also higher than the USEPA, European Union (EU), World Health Organisation (WHO) and World Bank standards (Table 2) at most of the monitoring stations, and $SO_2$ and $NO_x$ concentrations were also well within the international standards. Therefore, an effective action plan is required to control and manage air pollution in the residential areas surrounding the mines, where the people are directly exposed to a high concentration of particulate matter.

## Action plan for management

The air quality of the Ib Valley area has deteriorated and implementation of effective control measures is needed. Apart from the regular environmental control measures adopted by the mining company, a few additional measures might aid the control of air pollution at vulnerable sites (Table 3). CMRI[32] provide details of control measures and the technical reasons for the recommendation of a particular measure for a specific site. Truck loading restrictions and regular road cleaning are essential in order to control dust pollution from transportation, together with regular water spraying on roads. At almost all the locations, the sprinkling system was observed to be faulty. Regular maintenance/repair of the sprinkling system and construction of a more effective sprinkling system, along with application of a binding agent on the unpaved roads, are essential. In addition, unpaved roads should be converted to black-topped roads, with regular maintenance/repair of roads and the imposition of speed limits on trucks and other vehicles. Biological reclamation of overburden dumps and wastelands is also essential. Effective control measures at the coal handling plant, excavation area and overburden dumps should also be implemented to mitigate the SPM emissions at source.

A new approach adopted in recent years has involved the growth of green plants in and around the source of pollution. A green belt is the mass of pollutant-tolerant trees (evergreen and deciduous) for the purpose of mitigating the air pollution in an effective manner by filtering, intercepting and absorbing pollutants.[26] The capacity of plants to reduce air pollution is well known.[26,57] Optimum green belt development, including factors such as distance of green belt from source, width and height of green belt, may be achieved using an existing green belt attenuation model.[24,51] The likely effectiveness of a green belt in attenuating the pollution is given by the attenuation factor, which is defined as the ratio of mass flux reaching a particular distance in the absence of the green belt, to the mass flux reaching the same distance in the presence of the green belt.[24] However, the selection of tree species that can be grown around a mining site is very important. Plants differ considerably in their responses towards pollutants, some being highly sensitive and others hardy and tolerant.[25,51,58]

Few plant species can be grown around highly polluting sources in areas where dust (SPM) is the main pollutant; which not only controls air pollution but also retards water and soil contaminates. The green belt can help to control and check the dust on the surface, the leaves and bark, and can also tolerate $SO_2$ and $NO_x$ (gaseous pollutants) effectively.[59] India has a host of varieties of plant species that, if planted, would probably serve locally to lower atmospheric SPM, $SO_2$ and $NO_x$. Dust attenuating plant species should be used to develop green belt.[51]

In addition to the above measures for controlling air pollutants at source, there is a need for strict enforcement of existing air pollution laws to bring down the air pollutants level within the NAAQS and enforcement of compliance monitoring mechanism by various statutory bodies like Central and State Pollution Control Boards, Indian Bureau of Mines and Ministry of Environment and Forests. For effective implementation and monitoring of air control measures proper motivation and willingness of politicians are essential. The government of India has recognised the fact and recently a task force is constituted to modify the existing rules and regulations for better management of environmental quality in the mining areas and strengthen the mechanisation for effective implementation and monitoring of the environmental control measures at various mining areas in India.

**Table 3** Suggested mitigative measures at different locations of the Ib Valley area

| Station code | Location | Additional recommended control measures[a] |
|---|---|---|
| A1 | Gopi vihar colony | R1–R3, R8, R9, R11 |
| A2 | Kudopali village | R1–R3, R8, R11 |
| A3 | Orampara village | R1–R3, R8, R11 |
| A4 | Samleswari colony | R3, R8, R11 |
| A5 | Lajkura village | R3, R8, R11 |
| A6 | Madhuban nagar, rehabilitation site of Lajkura OCP | R3, R8, R11 |
| A7 | Lajkura VIP guest house | R1–R3, R8, R11 |
| A8 | Brajraj nagar market | R3, R8, R11 |
| A9 | General Manager complex of Ib valley area | R3, R8, R11 |
| A10 | Railway siding of Samleswari OCP | R1–R3, R5–R9, R11, R16 |
| A11 | Project office of Samleswari OCP | R1–R3, R8, R11, R16 |
| A12 | Coal handling plant of Lajkura OCP | R1–R13, R16 |
| A13 | Project office of Lajkura OCP | R1–R6, R8–R11, R14–R16 |
| A14 | Khairkuni village | R3, R8, R11 |
| A15 | TRL village | R1–R3, R8, R11 |
| A16 | Pipalmal village | R3, R8, R11 |
| A17 | Coal handling plant of Lilari OCP | R1–R13, R16 |
| A18 | Project office of Lilari OCP | R1–R8, R11, R14–R16 |

[a] R1 – Check/stop overloading of trucks/dumpers; R2 – Use of covered transportation; R3 – Regular cleaning of roads; R4 – Remote control sprinkling system on haul road and transport road; R5 – Effective use and maintenance of sprinkling system; R6 – Arrangement for additional sprinkling system; R7 – Regular maintenance of all heavy earth moving machinery and other machinery; R8 – Vehicular emission norms to be strictly enforced; R9 – All major roads to be metalled and properly maintained; R10 – Application of chemical binder in the haul road; R11 – Regular watering on haul road, transport road and other roads; R12 – Mechanical dust aerators/collectors to be installed wherever possible; R13 – Crushers of coal handling plants to be enclosed and dust control equipment should be deployed; R14 – Old inactive overburden dumps to be properly reclaimed and revegetated biologically using both grass and plant species; R15 – Active overburden dumps to be properly wetted to avoid wind erosion; and R16 – Implementation of greenbelt around different mining activities.

## Conclusions

SPM and RPM were the major sources of emission from various opencast mining activities, whereas emissions of $SO_2$ and $NO_x$ were negligible. The annual and 24 h average concentrations of SPM and RPM were higher than the NAAQS at most of the places both in the mining and residential areas. In opencast coal mining areas with similar conditions, the linear regression of SPM with RPM may be used for benchmarking the concentration of one type of particulate matter by knowing the level of the other.

Air quality in the Ib Valley area has exceeded the standard limit in spite of regular environmental control measures adopted by the mining company. A few more additional measures are required at the respective sensitive sites to control generation of particulate matters at source and a green belt should also be developed in and around the polluting sources. With the implementation of additional control measures at appropriate sites, the air quality in the study area could be brought within the national ambient air quality protocol threshold limit. Constructive measures at political level is essential to create motivation for implementation of various control measures and also to reduce the air pollution level in the mining area. This would lead to eco-friendly mining and better habitat for all those living in the area.

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