Environ Geol (2007) 51: 1177–1196
DOI 10.1007/s00254-006-0409-8

ORIGINAL ARTICLE

Bhabesh C. Sarkar
Bashab N. Mahanta
Kalyan Saikia
Pradip R. Paul
Gurdeep Singh

Geo-environmental quality assessment in Jharia coalfield, India, using multivariate statistics and geographic information system

Received: 20 February 2006
Accepted: 12 June 2006
Published online: 11 July 2006

B. C. Sarkar (✉) · B. N. Mahanta
K. Saikia · G. Singh
Indian School of Mines,
Dhanbad 826004, Jharkhand, India
E-mail: bhabesh_sarkar2003@yahoo.co.in
E-mail: bhabeshsarkar2005@gmail.com
Tel.: +91-9431121653
Fax: +91-326-2210028

P. R. Paul
Central Mine Planning and Design Institute
Limited, RI–II, Koyla Nagar,
Dhanbad 826005 Jharkhand, India

Abstract A study on geo-environmental quality assessment in Jharia coalfield, India, has been attempted using multivariate statistical analysis and geographic information system (GIS) modelling techniques. Water quality index, calculated for each sample network station in the study area to assess the suitability of water for human consumption, revealed very poor to poor quality surface water and mine water. Air quality indexing indicated that there is no sample station with clean air as per the Indian standards, which indicate the hazardous air quality. Multi-criteria evaluation (MCE), a potential GIS tool, has been applied to the delineation of various degrees of stressed villages in terms of quality of life (QoL). The role of various geo-environmental parameters such as quality of groundwater, surface water, mine water and air together with village population densities has been emphasized for delineation of the environmentally stressed villages in Jharia coalfield. The integrated cluster analysis and MCE approach provide an improved means to geo-environmental quality assessment in Jharia coalfield in terms of QoL. The assessment study is aimed to be used for future coal mining, ensuring ecologically sustainable industrial development, particularly in a coal-field.

Keywords Jharia coalfield · Geo-environment · Multivariate statistics · GIS

Introduction

The issues confronting today are faced with achieving desired development for economic or social reasons on one hand and safeguarding the environment and maintaining good quality of life (QoL) on the other. While emphasizing the need for developmental activities, the assimilative capacities of the geo-environmental components, i.e. air, water and land, to various types of pollution and environmental degradation are considered but with inadequate attention. The developmental activities, if haphazard and uncontrolled, lead to overuse, congestion, incompatible land use and poor living conditions. The problems of environmental pollution due to mining are becoming more and more complex (Karunakaram 1982). In Jharia coalfield, owing to unplanned mining history for several years prior to 1970 and urban sprawl and haphazard human settlement, there has been environmental degradation resulting in the deterioration of the QoL.

In the present paper, an attempt has been made to assess the QoL in reference to geo-environmental degradation due to mining in Jharia coalfield. The assessment has been made by identifying the environmentally affected areas of varying degrees, employing univariate and multivariate statistics, quality indexing and GIS overlay analysis. The study also aims to demonstrate the applicability and usefulness of GIS in geo-environmental assessment and its appropriateness for delineation of environmentally affected zones in Jharia coalfield while ensuring ecologically sustainable development.

Jharia coalfield: the study area

Jharia coalfield, located in Dhanbad district of Jharkhand state, is one of the single largest coalfields in India that has been actively associated with coal mining activities for more than a century. The study area lies in the heart of Damodar valley along the north of Damodar river. The coalfield is named after the chief mining centre, Jharia, situated in the eastern part of the coalfield. The coal basin extends for about 38 km in the east–west direction and a maximum of 18 km in the north–south direction covering an area of about 450 km^2. In view of large population and unhygienic condition around Jharia coal belt, active population of the Jharia coalfield faces acute shortage of clean drinking water and fresh air. The coalfield covers a semi-arid tract. Some parts of the coalfield experience drought so much so that the habitats use mine-discharged water as potable water. It is in this context that an attempt has been made by the present authors to delineate areas stressed with degraded environment, caused by coal mining activities in the coalfield.

The coalfield falls within the Survey of India topographic map numbers 73 I/1, I/2, I/5 and I/6 and is bounded within latitudes 23° 39′N and 23° 48′N and longitudes 86° 11′E and 86° 27′E covering an area of 450 km^2. The location map of the coalfield is shown in Fig. 1.

A brief geological description of the study area

In the study area, Precambrian basement metamorphic rocks are overlain by Talchir Formation and is followed upward by Barakar Formation which is the main coal-bearing horizon. This in turn is overlain by Barren Measures and followed upward by Raniganj Formation, which is the second coal-bearing horizon in the coalfield. A generalized regional chrono-stratigraphic succession of Jharia coalfield (Chandra 1992) is given in Table 1.

Data collection

In the present study, a part of the groundwater data has been collected through various field visits undertaken by the authors to the collieries and nearby localities of Jharia coalfield while remaining data have been collected from various sources. The analysis data of geochemical constituents in respect of groundwater, surface water and population density of Jharia coalfield have been collected from the Department of Environmental Engineering, Bharat Coking Coal Ltd, Koyla Nagar, Dhanbad. The surface water samples at sampling points 14, 20, 21, 22, 28, 32A, 38, 68, 93, 138 and 144 are collected from rivers and the rest are from local ponds. The analysis data of constituents of mine water and air of Jharia coalfield were collected from the Center of Mining Environment, Indian School of Mines. Samples of mine water were collected from areas of coal production in the mines where water gets accumulated and eventually pumped out to the surface.

Integrated approach to geo-environmental quality assessment

The methodology adopted in the present study integrates multivariate statistics, quality indexing and GIS-based overlay analysis of thematic maps. Cluster analysis (a multivariate statistical tool), also called segmentation analysis (or taxonomy analysis), aims to identify homogeneous subgroups in a population. In other words, cluster analysis identifies a set of groups which minimize within-group variation and maximize between-group variation. Cluster analysis is of two types based on the method of clustering, viz. hierarchical clustering and *k*-means clustering. In *hierarchical clustering*, a linking procedure of forming clusters is selected in terms of similarity measures, which determine how many clusters best suit the data. *Hierarchical clustering* is appropriate for smaller samples (typically < 250). To perform hierarchical clustering, one needs to specify the measure of similarity for generating all possible clusters. The clusters are nested rather than being mutually exclusive, i.e. larger clusters are created at later stages containing smaller clusters that are created at earlier stages of agglomeration. On the other hand, in *k-means clustering*, the number of clusters is specified in advance and then calculated as to how to assign cases to the *k* clusters. The technique is very computer-intensive and is therefore preferred sometimes when data sets are very large (> 1,000). Quality indices of water and air have been calculated at sampling points following a two-step approach: first, the calculation of quality rating for each of the quality parameters and second, a summation of these sub-indices in the overall index.

The thematic maps considered in the present study comprised that of groundwater, surface water, mine water and air quality. An integration of these maps provides a combined influence of various geochemical constituents of water and air at sample locations derived through quality indexing. Population density map when overlaid on the derived integrated water and air quality map aided in the delineation of varying degrees of affected population zones owing to environmental degradation in the coalfield due to mining. The overlay analysis has been carried out employing multi-criteria evaluation (MCE) procedure.

Multi-criteria evaluation technique primarily concerns providing an index of evaluation through combination of information using several criteria. In case of

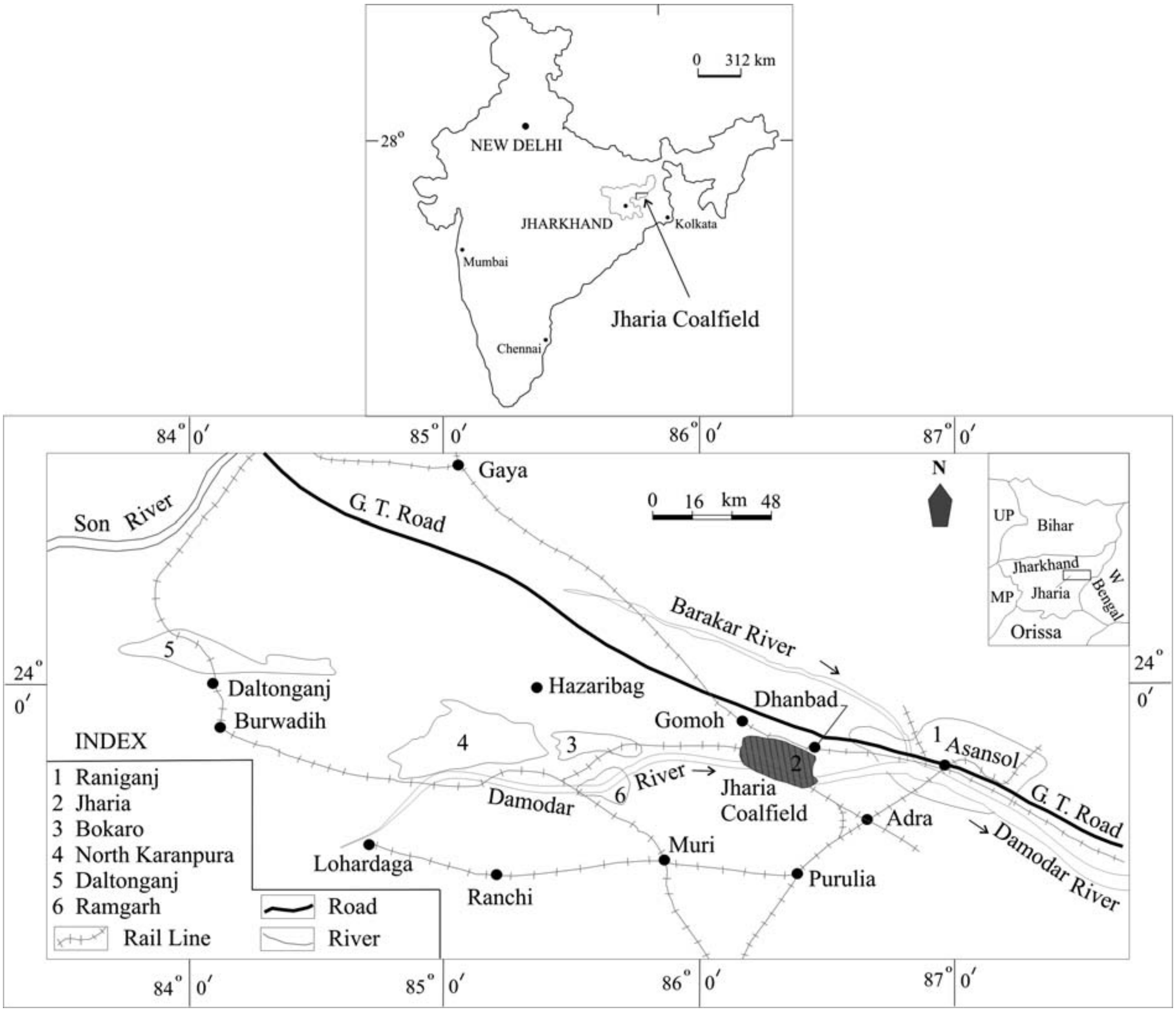

Fig. 1 Location map of Jharia coalfield—the study area

Boolean criteria (constraints), the solution usually lies in the union (logical OR) or intersection (logical AND) of conditions. However, for continuous factors, a weighted linear combination technique (Voogd 1983) is preferred. As the criteria are measured at different scales, they are standardized and transformed such that all thematic maps are positively correlated with suitability. In this technique, assigning of weights is the most difficult aspect, for which the most commonly used technique is the pair-wise comparison based on

Table 1 Generalized stratigraphic succession of Jharia coalfield (after Chandra 1992)

Age	Formation	Litho-type	Maximum thickness (m)
Jurassic or Tertiary		Dolerite dykes	
Lower Jurassic		Mica lamprophyre dykes and sills	
Upper Permian	Raniganj	Fine-grained feldspathic sandstones, shales with coal seams	800
Middle Permian	Barren Measures	Buff-coloured sandstones, shales and carbonaceous shales	730
Lower Permian	Barakar	Buff-coloured coarse and medium-grained feldspathic sandstones, grits, shales, carbonaceous shales and coal seams	1,250
Upper Carboniferous	Talchir	Greenish shale and fine-grained sandstones	245
Unconformity			
Archean	Metamorphics	Granite, granite-gneisses, quartzites, mica schists and amphibolites	

certain combination rules, viz. conjunction, disjunction and independence.

Multivariate statistical studies of water

Multivariate data can be defined as an observational unit characterized by several variables. An example of data appropriate for multivariate analysis is the chemical quality of water, which depends on factors like composition of host rock, slope of ground, movement of water, etc. Chemical characteristics of water play a vital role with respect to potable, agricultural and industrial purposes. Cluster analysis is one statistical tool to group similar pairs of correlation in a large symmetric matrix. It reduces a large data set into groups with similar characteristics. It provides logical and pair-by-pair comparison between various chemical constituents. The results of cluster analysis can be presented in a two-dimensional hierarchical diagram, on which the natural breaks between the groups become obvious. An observer can pick up groups at any desired level of similarity or dissimilarity (Miller and Kahn 1962; Parks 1966; Koch and Link 1970; Till 1974; Rao 2003).

Statistical treatment of data

To gain an understanding on the population parameters of various geochemical constituents of groundwater, surface water and mine water, the geochemical constituents have been treated for univariate statistical analyses, the results of which are provided in Tables 2, 3 and 4 for groundwater, surface water and mine water, respectively. The study revealed wide variations of values in respect of all the geochemical constituents of ground, surface and mine water except for pH. The percent variation around mean for pH of these waters is relatively low, i.e. 2.34, 2.24 and 1.91, respectively. The low value of percent variation around mean in respect of pH for the three types of water indicates consistency in the pH values of sampling points. The skewness of all three types of water is observed to be positive with a relative dominance of lower values of geochemical constituents except for pH of groundwater and mine water.

Cluster analysis has been carried out to substantiate the geo-interpretation of hydrogeochemical data. Cluster analysis has been useful in studying the similar pair groups of chemical constituents of water. The values of chemical constituents were subjected to *hierarchical cluster analysis*. Based on the indices of correlation coefficients, similar pair groups of chemical constituents have been linked and then the next most similar pair groups and so on, until all the chemical constituents have been clustered in a *dendrogram* by averaging method (Davis 1973; 1986).

Groundwater

A 16 × 16 matrix of correlation coefficients was computed to perform cluster analysis (Table 5). Correlation matrices of various stages of clustering were then obtained. In the first step of the cluster analysis, mutually highest correlation coefficients were identified from the initial linear correlation matrix. Next, similar highest correlation coefficients of chemical constituents in respect of pair groups such as Mg^{2+}–total hardness (TH) and Fe^{2+}–Zn^{2+} were clustered. The new correlation coefficients between Mg^{2+}–TH and Fe^{2+}–Zn^{2+} clusters and independent constituents were recalculated

Table 2 Statistical parameters of chemical constituents of groundwater

Sl no.	Variable	Minimum	Maximum	Mean	Standard deviation	Variance	Skewness	Kurtosis	95% confidence level	Variation around mean (%)
1	TDS (mg/l)	5.00	320.00	67.45	60.04	3,605.12	2.02	8.18	67.45 ± 15.50	22.98
2	pH	4.60	7.68	6.84	0.61	0.37	−1.57	5.66	6.84 ± 0.16	2.34
3	EC (μS/cm)	532.75	2,884.7	1,500.36	555.09	308,132.80	0.46	2.60	1,500.36 ± 143.32	9.55
4	Cl^- (mg/l)	9.22	875.75	121.60	117.19	13,733.71	4.53	28.95	121.6 ± 30.26	24.88
5	NO_3^+ (mg/l)	0.20	205.40	21.75	33.96	1,153.41	3.68	18.58	21.75 ± 8.77	40.32
6	Na^+ (mg/l)	6.00	160.40	50.32	34.06	1,160.61	1.37	4.54	50.32 ± 8.79	17.47
7	K^+ (mg/l)	0.55	92.40	12.61	16.51	272.77	2.92	12.77	12.61 ± 4.26	33.78
8	Ca^{2+} (mg/l)	16.36	175.60	62.88	30.40	924.46	1.07	4.85	62.88 ± 7.85	12.48
9	Mg^{2+} (mg/l)	4.40	174.50	58.04	34.29	1,175.02	1.14	4.12	58.04 ± 8.85	15.25
10	TH (mg/l)	53.00	936.00	376.94	182.09	33,159.68	0.80	3.32	376.94 ± 47.02	12.47
11	Cu^{2+} (mg/l)	0.002	0.21	0.02	0.03	0.0009	4.11	23.41	0.02 ± 0.008	40.00
12	Fe^{2+} (mg/l)	0.001	11.94	0.48	1.68	2.83	5.74	37.33	0.48 ± 0.43	89.58
13	Zn^{2+} (mg/l)	0.01	3.95	0.16	0.52	0.27	6.56	47.57	0.159 ± 0.13	81.76
14	SO_4^{2-} (mg/l)	14.00	88.30	100.93	122.45	14,996.00	4.48	28.10	100.93 ± 31.62	31.33
15	CO_3^{2-} (mg/l)	1.80	653.00	77.09	111.67	12,469.49	4.54	23.52	77.09 ± 28.83	37.40
16	HCO_3^- (mg/l)	3.00	352.00	159.90	79.29	3,287.00	0.26	3.03	159.9 ± 20.47	12.80

Table 3 Statistical parameters of chemical constituents of surface water

Sl no.	Variable	Minimum	Maximum	Mean	Standard deviation	Variance	Skewness	Kurtosis	95% confidence level	Variation around mean (%)
1	TDS (mg/l)	5.00	885.00	108.63	163.89	26,861.89	3.07	13.55	108.63 ± 54.63	50.29
2	pH	6.83	9.71	8.03	0.53	0.28	0.36	4.20	8.03 ± 0.18	2.24
3	EC (μS/cm)	232.0	2,048.0	1,027.76	520.64	271,073.00	0.52	2.08	1,027.76 ± 173.55	7.16
4	Cl^- (mg/l)	8.30	222.00	43.88	45.44	2,065.63	2.71	10.47	43.88 ± 15.15	34.53
5	Na^+ (mg/l)	4.06	196.40	44.18	33.78	1,140.95	2.67	11.74	44.18 ± 11.26	25.49
6	K^+ (mg/l)	0.01	64.60	13.17	11.99	143.86	2.22	9.28	13.17 ± 4.00	30.37
7	Ca^{2+} (mg/l)	6.90	100.10	44.87	23.46	550.34	0.81	2.96	44.87 ± 7.82	17.43
8	Mg^{2+} (mg/l)	3.80	136.90	40.36	33.13	1,098.13	1.50	4.67	40.36 ± 11.04	27.35
9	SO_4^{2-} (mg/l)	41.60	867.00	255.61	181.25	32,853.40	1.34	4.67	255.61 ± 60.42	23.64
10	Fe^{2+} (mg/l)	0.01	0.82	0.12	0.18	0.03	3.54	12.05	0.12 ± 0.06	50.00
11	Mn^{2+} (mg/l)	0.01	3.29	0.38	0.52	0.27	5.19	29.60	0.38 ± 0.17	44.74

Table 4 Statistical parameters of chemical constituents of mine water

Sl no.	Variable	Minimum	Maximum	Mean	Standard deviation	Variance	Skewness	Kurtosis	95% confidence level	Variation around mean (%)
1	TDS (mg/l)	286.00	1,020.00	676.50	163.14	26,613.03	0.22	3.02	676.50 ± 58.63	8.67
2	pH	6.40	7.80	7.18	0.382	0.15	− 0.41	2.39	7.18 ± 0.14	1.91
3	EC (μS/cm)	101.00	7,121.0	1,381.65	1,137.12	1,393,060.00	3.89	20.43	1,381.65 ± 408.6	29.58
4	Cl^- (mg/l)	18.00	69.00	33.37	14.77	218.04	1.01	2.98	33.37 ± 5.31	15.91
5	NO_3^- (mg/l)	0.10	6.40	0.99	1.47	2.15	2.90	10.85	0.99 ± 0.53	53.36
6	Na^+ (mg/l)	8.00	45.00	16.84	8.84	78.07	1.68	5.34	16.84 ± 3.18	18.87
7	K^+ (mg/l)	1.00	9.00	3.21	1.62	2.63	1.41	5.80	3.21 ± 0.58	18.14
8	TH (mg/l)	128.00	670.00	376.13	132.02	17,431.40	0.16	2.62	376.13 ± 47.45	12.61
9	Cu^{2+} (mg/l)	0.010	0.61	0.04	0.10	0.01	4.98	27.17	0.04 ± 0.04	89.85
10	Zn^{2+} (mg/l)	0.004	1.30	0.17	0.24	0.06	3.20	15.31	0.17 ± 0.09	50.74
11	Mn^{2-} (mg/l)	0.002	0.17	0.04	0.41	0.002	1.53	4.44	0.04 ± 0.15	368.37
12	Fe^{2+} (mg/l)	0.001	3.93	0.22	0.69	0.47	4.95	26.85	0.22 ± 0.25	112.72
13	SO_4^{2-} (mg/l)	26.00	264.00	90.44	45.32	2,054.70	1.68	7.50	90.44 ± 16.29	18.01

Table 5 Correlation matrix of first stage for groundwater

	TDS	pH	EC	Cl^-	NO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	TH	Cu^{2+}	Fe^{2+}	Zn^{2+}	SO_4^{2-}	CO_3^{2-}	HCO_3^-
TDS	1															
pH	−0.037	1														
EC	−0.194	0.109	1													
Cl^-	0.016	0.109	0.375	1												
NO_3^-	0.045	0.01	0.026	0.115	1											
Na^+	−0.094	0.294	0.486	0.514	0.053	1										
K^+	0.047	0.128	0.465	0.337	0.056	0.469	1									
Ca^{2+}	−0.013	0.079	0.467	0.323	0.133	0.516	0.399	1								
Mg^{2+}	−0.152	0.396	0.452	−0.014	−0.064	0.375	0.176	0.208	1							
TH	−0.129	0.373	0.589	0.127	0.023	0.541	0.341	0.545	0.908	1						
Cu^{2+}	0.308	−0.157	−0.002	−0.069	−0.047	−0.019	0.121	0.073	0.015	0.042	1					
Fe^{2+}	0.48	−0.180	−0.111	−0.024	−0.02	−0.074	0.081	0.023	−0.14	−0.084	0.811	1				
Zn^{2+}	0.405	−0.181	−0.079	0.0005	0.002	−0.035	0.112	0.022	−0.19	−0.127	0.771	0.882	1			
SO_4^{2-}	−0.125	0.133	−0.147	0.017	−0.079	−0.092	−0.074	−0.27	−0.15	−0.207	−0.143	0.033	−0.064	1		
CO_3^{2-}	0.189	−0.035	0.038	0.165	0.07	0.046	0.026	0.359	−0.16	−0.023	0.532	0.59	0.647	−0.09	1	
HCO_3^-	0.131	−0.293	−0.223	0.172	−0.048	−0.133	−0.031	−0.22	−0.4	−0.44	−0.071	0.007	0.064	0.028	−0.18	1

by averaging method as given by Davis (1973, 1986). Remaining correlation coefficients of individual constituents were retained. Cu^{2+} and Fe^{2+}–Zn^{2+} were then clustered considering Fe^{2+}–Zn^{2+} as a paired group. In this step, Na^+–Ca^{2+} were clustered. New correlation coefficients among Mg^{2+}–TH, Na^+–Ca^{2+} and

Fe^{2+}–Zn^{2+}–Cu^{2+} clusters and independent constituents were recalculated. In the subsequent step, electrical conductivity (EC)–Mg^{2+}–TH and Cu^{2+}–Fe^{2+}–Zn^{2+}–CO_3^{2-} were clustered. Next, TDS was clustered with Cu^{2+}–Fe^{2+}–Zn^{2+}–CO_3^{2-}, and Na^+–Ca^{2+} with Mg^{2+}–TH. Finally, the two clusters, viz. TDS–Cu^{2+}–Fe^{2+}–Zn^{2+}–CO_3^{2-}–NO_3^-–HCO_3^- and pH–EC–TH–Mg^{2+}–Na^+–Ca^{2+}–K^+–Cl^-–SO_4^{2-} were linked (Table 6). The resulting dendrogram is displayed in Fig. 2. The analysis indicates two broad *types* of groundwater, viz.

Type I : $Mg - TH{-}EC - Ca^{2+} - Na^+ - K^+ - Cl^- - pH{-}SO_4^{2-}$.

Type II : $Cu^{2+} - Fe^{2+} - Zn^{2+} - CO_3^- - TDS{-}NO_3^- - HCO_3^-$.

Surface water

An 11 × 11 matrix of correlation coefficients has been computed to perform cluster analysis of surface water (Table 7). Correlation matrices of various stages of clustering were then obtained. In the first step, as in the case of groundwater, mutually highest correlation coefficients were identified from the initial linear correlation matrix. Next, similar highest correlation coefficients of chemical constituents in respect of pair groups such as Mg^{2+}–pH and Na^+–K^+ were clustered. The new correlation coefficients between Mg^{2+}–pH and Na^+–K^+ clusters and independent constituents were recalculated by averaging method. Remaining correlation coefficients of individual constituents were retained. Cl^- and Na^+–K^+ were then clustered considering Na^+–K^+ as a combined element. In this step, EC–SO_4^{2-} were clustered. New correlation coefficients among Mg^{2+}–pH, EC–SO_4^{2-} and Na^+–K^+–Cl^- clusters and independent constituents were recalculated. Finally, the two clusters, viz. TDS–pH–Mg^{2+}–EC–SO_4^{2-}–Na^+–K^+–Cl^-–Ca^{2+} and Fe^{2+}–Mn^{2+} were linked (Table 8). The resulting dendrogram for surface water is shown in Fig. 3. The cluster analysis indicates two broad *types* of surface water in the study area, viz.

Type I : $TDS{-}pH{-}Mg^{2+} - EC - SO_4^{2-} - Na^+ - K^+ - Cl^- - Ca^{2+}$ or EC type water.

Type II : $Fe^{2+} - Mn^{2+}$ or iron type water.

Table 6 Correlation matrix of final stage for groundwater

	Cu^{2+}–Fe^{2+}–Zn^{2+}–CO_3^{2-}–TDS–NO_3^-–HCO_3^-	Mg^{2+}–TH–EC–Ca^{2+}–Na^+–K^+–Cl^{2-}-pH–SO_4^-
Cu^{2+}–Fe^{2+}–Zn^{2+}–CO_3^-–TDS–NO_3^-–HCO_3^-	1	
Mg^{2+}–TH–EC–Ca^{2+}–Na^+–K^+–Cl^-–pH–SO_4^{2-}	−0.058	1

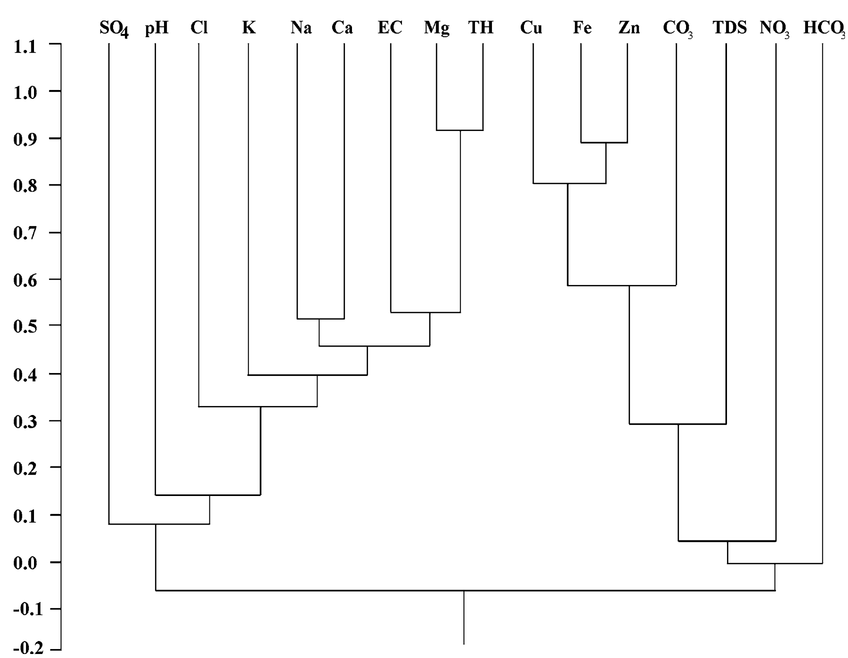

Fig. 2 Dendrogram for cluster analysis of groundwater

Table 7 Correlation matrix of first stage for surface water

	TDS	pH	EC	Cl^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	SO_4^{2-}	Fe^{2+}	Mn^{2+}
TDS	1										
pH	0.012	1									
EC	0.034	0.231	1								
Cl^-	−0.070	−0.083	0.540	1							
Na^+	−0.030	0.202	0.446	0.611	1						
K^+	0.169	0.102	0.429	0.508	0.740	1					
Ca^{2+}	0.065	0.044	0.265	0.048	−0.100	0.120	1				
Mg^{2+}	0.136	0.246	0.138	0.049	0.070	0.120	0.168	1			
SO_4^{2-}	0.199	0.132	0.580	−0.106	0.221	0.080	−0.080	0.005	1		
Fe^{2+}	−0.141	−0.068	−0.218	−0.159	−0.072	0.412	−0.118	−0.140	−0.233	1	
Mn^{2+}	−0.142	−0.016	−0.130	−0.027	−0.001	−0.214	−0.132	−0.140	−0.114	−0.031	1

Table 8 Correlation matrix of final stage for surface water

	TDS–pH–Mg^{2+}–EC–SO_4^{2-}–Na^{2+}–K^+–Cl^-–Ca^{2+}	Fe^{2+}–Mn^{2+}
TDS–pH–Mg^{2+}–EC–SO_4^{2-}–Na^{2+}–K^+–Cl^-–Ca^{2+}	1	
Fe^{2+}–Mn^{2+}	−0.130	1

The type I water includes two *subtypes* of water, viz.

Subtype I : $EC{-}SO_4^{2-} - Na^+ - K^+ - Cl^-$.
Subtype II : $pH{-}Mg^{2+}$.

Mine water

To perform cluster analysis of mine water, a 13 × 13 matrix of correlation coefficients was computed

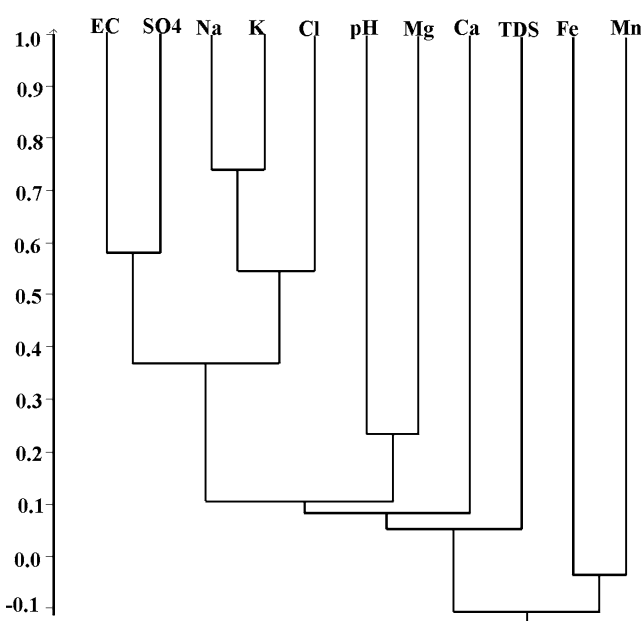

Fig. 3 Dendrogram for cluster analysis of surface water

(Table 9). Correlation matrices of various stages of clustering were then generated. In the first step, as in the cases of groundwater and surface water, mutually highest correlation coefficients were identified from the initial linear correlation matrix. Next, similar highest correlation coefficients of chemical constituents in respect of pair groups of TH–SO_4^{2-}, Mn^{2+}–NO_3^- and Zn^{2+}–Na+ were clustered. The new correlation coefficients between TH–SO_4^{2-}, Mn^{2+}–NO_3^- and Zn^+–Na^+ clusters and independent constituents were recalculated. Remaining correlation coefficients of individual constituents were retained. TDS and TH–SO_4^{2-} were then clustered considering TH–SO_4^{2-} as a paired group. Finally, the two clusters, viz. pH–Cl^-–TDS–TH–SO_4^{2-}–Fe^{2+}–Zn^{2+}–Na^+–K^+ and EC–Cu^{2+}–Mn–NO_3^- were linked (Table 10). The resulting dendrogram is shown in Fig. 4. The cluster analysis for mine water also indicates two broad *types* of mine water, viz.

Type I : $pH{-}Cl^- - TDS{-}TH{-}SO_4^{2-} - Fe^{2+} - Zn^{2+} - Na^+ - K^+$.
Type II : $EC{-}Cu^{2+} - Mn^{2+} - NO_3^-$.

Water quality studies

Coal mining requires large amount of water for various purposes including dust control, fire protection and coal washing. The average use of water in coal mining varies from 63 to 120 l per metric tonne in underground mining and about 17 l per tonne for surface mining (Hinawi 1981). In addition to this, 33 l of water per tonne is required for waste disposal both in surface and

Table 9 Correlation matrix of first stage for mine water

	pH	EC	TDS	TH	Cu^{2+}	Zn^{2+}	Mn^{2+}	Fe^{2+}	Cl^-	SO_4^{2-}	NO_3^-	Na^+	K^+
pH	1												
EC	0.084	1											
TDS	0.445	−0.210	1										
TH	0.331	−0.130	0.638	1									
Cu^{2+}	0.099	0.064	0.020	0.028	1								
Zn^{2+}	0.180	−0.089	0.241	−0.003	−0.099	1							
Mn^{2+}	−0.112	−0.151	−0.171	0.025	−0.201	0.041	1						
Fe^{2+}	0.305	−0.185	0.403	0.129	−0.071	0.103	−0.123	1					
Cl^-	0.383	−0.056	0.419	0.338	−0.126	0.197	0.300	0.143	1				
SO_4^{2-}	0.128	−0.037	0.389	0.710	−0.090	−0.173	0.143	0.157	0.286	1			
NO_3^-	0.014	0.050	0.012	0.095	−0.127	−0.021	0.488	0.011	−0.055	0.089	1		
Na^+	0.268	−0.051	0.306	0.101	−0.192	0.605	−0.119	−0.053	0.147	0.154	−0.122	1	
K^+	−0.076	−0.169	0.182	0.133	−0.153	0.065	−0.242	0.213	0.029	−0.080	−0.293	0.180	1

Table 10 Correlation matrix of final stage for mine water

	pH–Cl^-–TDS–TH–SO_4^{2-}–Fe^{2+}–Zn^{2+}–Na^+–K^+	EC–Cu^{2+}–Mn^{2+}–NO_3^-
pH–Cl^-–TDS–TH–SO_4^{2-}–Fe^{2+}–Zn^{2+}–Na^+–K^+	1	
EC–Cu^{2+}–Mn^{2+}–NO_3^-	−0.132	1

underground mining. When this water drains through a large area of the mine, it carries with it soluble minerals that may be present either in the coal or associated rocks, thus causing severe degradation of water quality. Coal processing also causes serious water pollution. The black water produced through coal washing is a potential pollutant if it is discharged into streams without treatment (Krishnamurthy 2004; Chadwick et al. 1987).

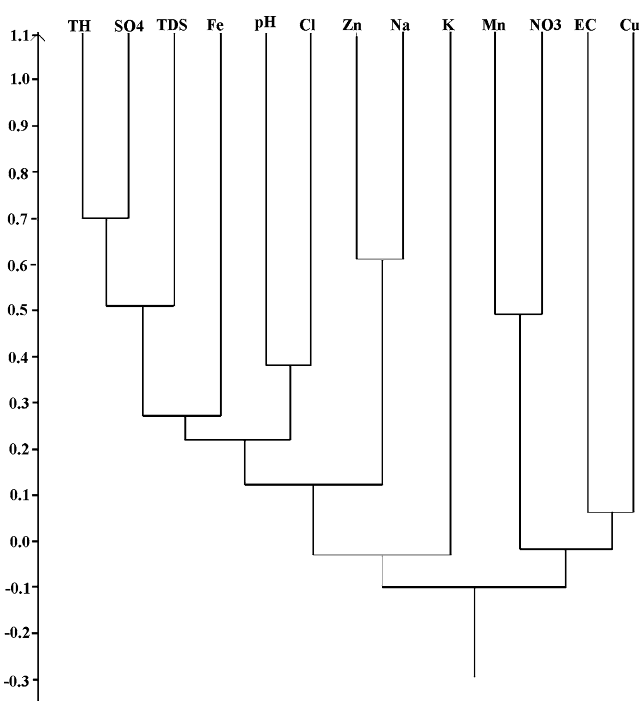

Fig. 4 Dendrogram for cluster analysis of mine water

Water pollution can be controlled if adequate care is taken to ensure that the discharged water from the mines and associated industries does not carry chemical compounds. Chemical analysis provides a better understanding of the chemical aspect of water. This can also permit planning for necessary treatment that may be required to cope up with future changes in the quality of water.

Water quality index

Water quality and its suitability for drinking purpose can be examined by determining its quality index. Water quality index (WQI) is defined as a technique of rating that provides the composite influence of individual water quality parameter on the overall quality of water. It is calculated from the point of view of human consumption. The standards for drinking purpose as recommended by ISI (Rao 1997) have been considered for calculation of WQI. The weights for various water quality parameters are assumed to be inversely proportional to the recommended standards (Table 11) for the corresponding parameters (Rao 1997; Mishra and Patel 2001; Naik and Purohit 2001; Rao et al. 2002; Mahanta et al. 2004). The formulation for weight calculation is given by the expression:

$$w_i = k/s_i,$$

where w_i is the unit weight for the ith parameter; s_i the recommended standard for parameter and

Table 11 Chemical parameters with corresponding Indian standards (for drinking purpose)

Chemical parameter	Standards as per ISI	$w_i = k/s_1$
pH	7.0–8.50	0.00423
EC (μmho/cm)	300	0.0001
TDS (mg/l)	500–1,500	0.00006
Cl^- (mg/l)	250–1,000	0.00012
TH (mg/l)	300–600	0.0001
SO_4^{2-} (mg/l)	150–400	0.0002
Ca^{2+} (mg/l)	75–200	0.00039
Mg^{2+} (mg/l)	30–100	0.0001
Na^+ (mg/l)	200	0.00015
K^+ (mg/l)	50	0.00059
Fe^{2+} (mg/l)	0.3–1.0	0.0987
Mn^{2+} (mg/l)	0.1–0.5	0.2961
Cu^{2+} (mg/l)	0.05–1.5	0.5922
Zn^{2+} (mg/l)	5.0–15.0	0.00592
		$\sum =$ 0.99886

$i = 1, 2, 3, ..., 16$; and k the constant of proportionality (Kumar 2002).

The calculation involves the following steps:

(a) First, the calculation of the quality rating for each of the water quality parameters
(b) Second, a summation of these sub-indices in the overall index

Individual quality rating is given by the expression:

$$q_i = 100v_i/s_i,$$

where v_i is the measured value of the ith parameter in groundwater sample under consideration and s_i the standard or permissible limit for the ith parameter.

The WQI is then calculated as follows:

$$\mathrm{WQI} = \sum_{i=1}^{n}(q_i w_i)/\sum_{i=1}^{n} w_i.$$

Indian standards as per ISI for drinking water together with its corresponding status categories of WQI (Rao 1997) are given in Tables 11 and 12, respectively. The sample network stations for groundwater, surface water and mine water are shown in Figs. 5, 6 and 7. Water quality indices calculated individually for sampling points in respect of groundwater, surface water and mine water along with water status are given in Tables 13, 14 and 15.

Air quality studies

Air pollution may be defined as the presence of one or more contaminants or combination in the outdoor atmosphere in such quantities and of duration which may be or tend to be injurious to human beings or other living creatures or plants or to the atmosphere itself.

Table 12 Status categories of WQI

WQI	Status
0–25	Very good
26–50	Good
51–75	Poor
> 75	Very poor

Air pollution in mining area is very typical. There are many sources of air pollution in mining complexes, viz. open cast mines, underground mines, thermal power plants, washery, diesel engines, light and heavy vehicles. Main pollutants released due to mining are mostly gaseous or particulate. Particulate are non-gaseous substances consisting of dust, other solid vapour bubbles and liquid floating in the air that almost act as gaseous molecules in many respects.

The effects of air pollutants on the environment depends on the chemical and physical properties of pollutants as well as the dilution and dispersion capabilities of the prevalent ambient meteorological condition in the area. Pollution dilution in the atmosphere may be considered as a function of their density, atmospheric stability conditions and wind speed (Frangi 1996).

Air pollutants can be classified into two broad groups—primary and secondary air pollutants.

Primary pollutants These are the pollutants emitted into the atmosphere directly from identifiable sources and are found in the atmosphere in the same chemical form as that at the time of emission from the source. Finer particles (less than 100 μm in diameter), coarse particles (greater than 100 μm in diameter), sulphur compounds, oxides of nitrogen, carbon monoxide, halogen compounds, organic and radioactive compounds are some of the primary pollutants.

Secondary pollutants Secondary pollutants are produced in the air by the interaction among two or more primary pollutants or by the reaction with normal atmospheric constituents, with or without photoactivation. Ozone, formaldehyde, photochemical smog are some of the secondary pollutants.

In the air sampling procedure, prevailing wind direction has been taken care of. Because the present study aims at emphasizing an integrated approach to the application of multivariate statistics and GIS for geo-environmental quality assessment in Jharia coalfield, combined impacts of water and air pollution on QoL in the coalfield due to mining have been thought appropriate to aid in the delineation of environmentally stressed areas despite less number of air sampling stations.

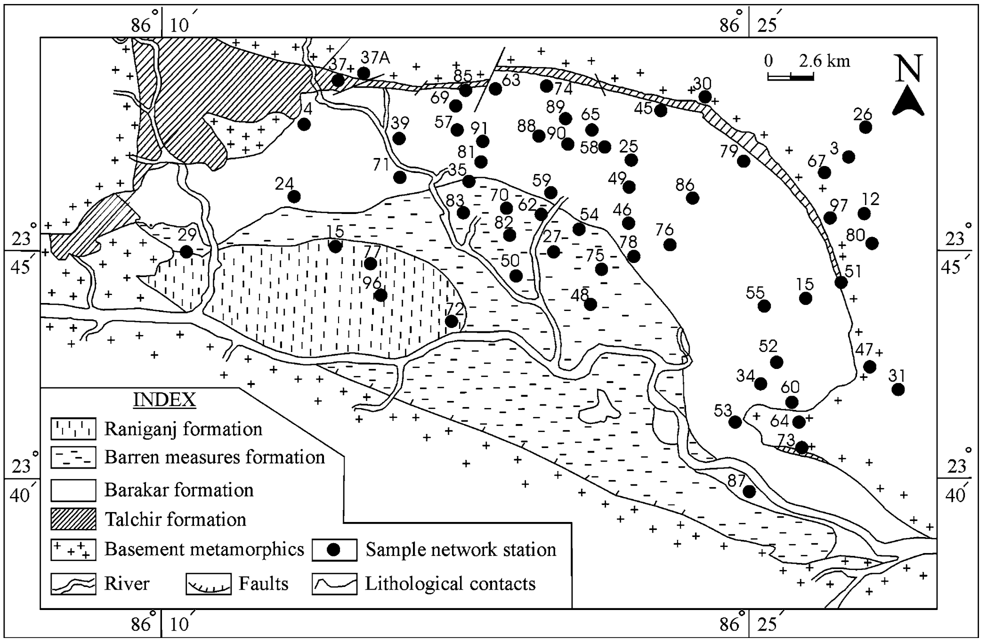

Fig. 5 Geological map of Jharia coalfield with groundwater sample network stations

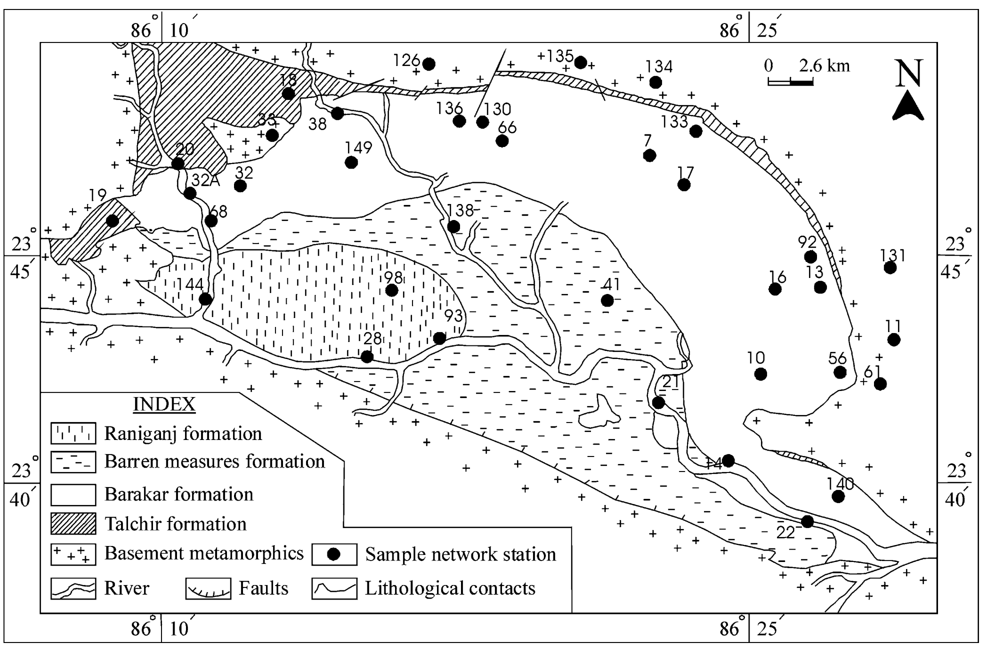

Fig. 6 Geological map of Jharia coalfield with surface water sample network stations

Air quality index

The air quality standards for different pollutants differ widely from country to country. There is a necessity to describe the air quality based on the cumulative effect of all the pollutants, as the synergistic effect of all the pollutants are more severe than the effect of the individual pollutant. Based on this assumption, seven categories have been identified to describe the ambient air quality index (AQI). The National Ambient Air Quality Standards and the classification of AQI (Gogoi 1999) are shown in Tables 16 and 17.

In arriving at AQI of an area, an important assumption that all the pollutant parameters are of

Fig. 7 Geological map of Jharia coalfield with mine water sample network stations

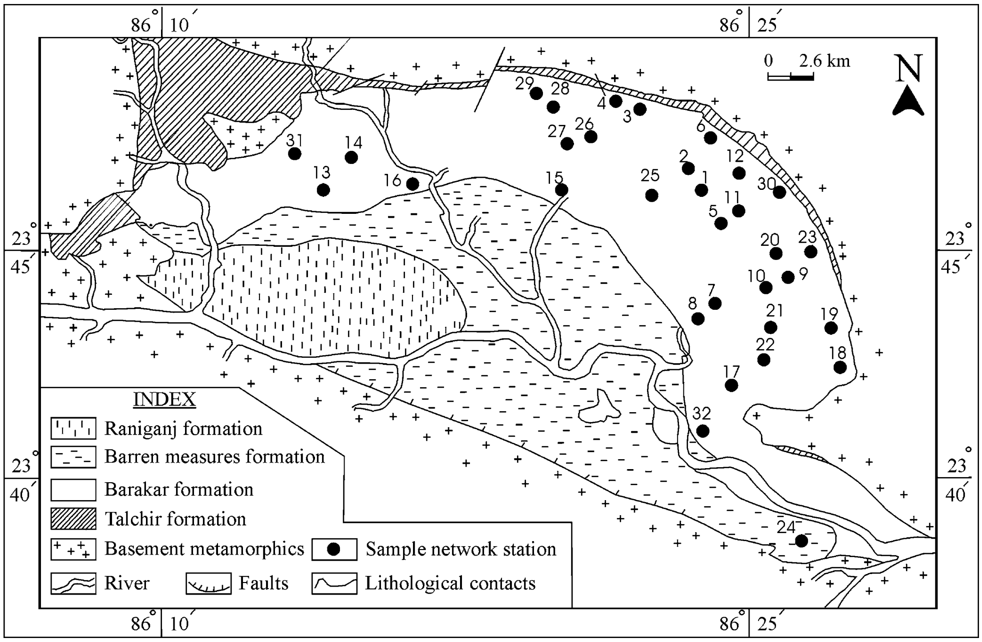

Table 13 Calculated water quality index (WQI) for individual groundwater sampling station

Network station	WQI	Water status	Network station	WQI	Water status	Network station	WQI	Water status
3	52.682	Poor	46	98.156	Good	65	48.590	Very poor
4	40.203	Very good	47	126.20	Good	67	94.609	Very poor
12	36.814	Good	48	18.329	Good	69	15.711	Very good
15	64.175	Poor	49	41.945	Good	70	25.933	Good
24	0.927	Very poor	50	22.294	Very good	71	14.972	Good
25	32.190	Good	51	45.845	Very good	72	82.236	Very good
26	29.532	Good	52	395.70	Good	73	41.276	Good
27	12.811	Very good	53	16.926	Good	53	16.926	Good
29	10.447	Poor	54	0.541	Very poor	30	38.865	Good
30	38.865	Good	55	83.035	Poor	64	40.716	Good
31	47.218	Very good	57	46.596	Very poor	59	37.599	Good
34	94.147	Very good	58	46.833	Very poor	25	32.190	Good
35	33.563	Very good	59	37.599	Good	74	30.375	Good
37	10.523	Good	60	12.742	Good	75	201.22	Very good
37A	39.971	Very good	62	51.195	Good	76	35.312	Very good
39	42.757	Poor	63	51.249	Good	77	18.729	Very good
45	73.207	Good	64	40.716	Good	78	45.270	Good
79	31.274	Very good	83	46.804	Very good	88	42.315	Good
80	37.596	Poor	85	44.344	Very poor	90	31.431	Good
81	0.791	Good	86	74.047	Very good	91	3.666	Very poor
82	49.471	Good	87	912.63	Very good	96	13.799	Very good
97	7.109	Very poor						

equal importance is made. If there are 'n' air quality parameters, P_i = (1, 2, 3, ..., n), the air quality rating (Q_i) is given by the following expression:

$$Q_i = (V_i \times 100)/V_{\mathrm{si}},$$

where V_i is the observed value of parameter Q_i and V_{si} the standard value recommended for the parameter. If 'n' is the number of pollutant parameters considered for air quality, then n numbers of quality ratings are obtained for the observed values. The geometric mean of these individual air quality ratings is designated as AQI for that particular station.

In the present study, individual quality ratings (Q_i) of all the air pollutant parameters in respect of 13 sample stations have been calculated using the above-mentioned procedure. Based on these individual quality rating

Table 14 Calculated water quality index (WQI) for individual surface water samples

Network station	WQI	Water status	Network station	WQI	Water status	Network station	WQI	Water status
7	12.282	Very good	28	116.158	Very poor	103	118.761	Very poor
10	104.108	Very poor	32	112.916	Very poor	126	109.882	Very poor
11	111.657	Very poor	33	115.884	Very poor	130	24.509	Very good
13	114.077	Very poor	32A	115.680	Very poor	131	117.232	Very poor
14	96.244	Very poor	38	122.201	Very poor	133	17.113	Very good
16	113.237	Very poor	41	114.807	Very poor	134	979.736	Very poor
17	44.933	Good	56	115.513	Very poor	135	115.977	Very poor
18	115.303	Very poor	61	115.503	Very poor	136	115.579	Very poor
19	58.357	Poor	66	116.196	Very poor	138	15.748	Very good
20	116.483	Very poor	68	114.457	Very poor	140	6.132	Very good
21	115.225	Very poor	92	213.727	Very poor	144	130.472	Very poor
22	52.316	Poor	98	115.857	Very poor	149	114.930	Very poor

Table 15 Calculated water quality index (WQI) for individual mine water samples

Network station	WQI	Water status	Network station	WQI	Water status	Network station	WQI	Water status
1	51.707	Poor	12	15.620	Very good	23	16.678	Very good
2	51.656	Poor	13	41.702	Good	24	50.426	Poor
3	40.537	Good	14	18.002	Very good	25	17.215	Very good
4	51.068	Poor	15	49.781	Good	26	49.468	Good
5	86.370	Very poor	16	51.983	Poor	27	729.302	Very poor
6	79.899	Very poor	17	29.721	Good	28	47.547	Very good
7	37.170	Good	18	29.326	Good	29	49.035	Good
8	26.706	Good	19	32.245	Good	30	47.275	Good
9	56.429	Poor	20	96.197	Very poor	31	40.796	Good
10	63.338	Poor	21	39.408	Good	32	52.806	Poor
11	149.919	Very poor	22	34.393	Good			

Table 16 National Ambient Air Quality Standards

Pollutant	Time-weighted average	Concentration in ambient air (μg/m^3)		
		Sensitive	Industrial	Residential
Sulphur oxide (SO_2^{2-})	Annual	15	80	60
	24 h	30	120	80
Oxides of nitrogen	Annual	15	80	60
	24 h	30	120	80
Suspended particulate matter (SPM)	Annual	70	360	140
	24 h	100	500	200
Respirable particulate matter (RPM)	Annual	50	120	60
	24 h	75	150	100
Lead (Pb^{2+})	Annual	0.50	1.0	0.75
	24 h	0.75	1.5	1.0
Cu^{2+}	Annual	0.50	1.0	0.75
	24 h	0.75	1.5	1.0
Fe^{2+}	Annual	0.50	1.0	0.75
	24 h	0.75	1.5	1.0

values, air quality indexing of the network stations has been carried out that resulted in categorization and determination of air status of all stations as per National Ambient Air Quality Standards. The result of air quality indexing of Jharia coalfield is given in Table 18. The sample network stations for air are shown in Fig. 8.

Geo-environmental assessment using GIS

The GIS has functional capabilities of data capture, input, manipulation, transformation, visualization, combination, query, analysis, modelling and output. In

Table 17 Classification of air quality index (ISI 1975)

Category	AQI	Description
I	< 10	Very clean
II	10–25	Clean
III	25–50	Fairly clean
IV	50–75	Moderately polluted
V	75–100	Polluted
VI	100–125	Heavily polluted
VII	> 125	Severely polluted

the present study, various thematic maps, namely, groundwater quality, surface water quality, mine water quality and air quality have been generated. Population density map of the study area has been generated from the census report of Dhanbad district. These maps have been digitized, edited, topology built and polygonized in SPANS Topographer software and subsequently thematic information layers have been generated for GIS overlay analysis.

Various thematic information layers that have been generated in GIS using various data input include:

1. Groundwater quality map
2. Surface water quality map
3. Mine water quality map
4. Air quality map
5. Population density map

In the present paper, GIS analyses have been carried out using SPANS software with kriging as an interpolation technique. The underlying mathematical concept of geostatistical interpolation technique known by the name ‘kriging’ is based on ‘theory of regionalized variable’ (ReV) developed by Matheron in 1960. According to this theory, a variable distributed in space and/or time exhibiting some degree of spatial correlation can be considered a regionalized variable. Thus, geochemical constituents of water and air considered in the present study for quality indexing and delineation of environmentally impacted zones are distributed in space and exhibit spatial correlation. Because of this, geostatistical kriging technique is considered to be the appropriate interpolation technique for providing best, linear and unbiased interpolated values at unsampled grids with minimum variance. As mining of coal mostly concentrated in the northern periphery of Jharia coalfield with seam occurring in Barakar Formation, most sample network stations are distributed within this limit. The interpolation was constrained in the coalfield with sample network stations located at irregular intervals. However, it may be mentioned that interpolation results may be further refined with addition of more sample networks covering the entire coalfield in a regular grid interval.

Table 18 Calculated air quality index (AQI) for individual air sampling locations

Network station	AQI	Category	Air status
1	79.02	V	Polluted
2	147.91	VI	Heavily polluted
3	163.22	VII	Severely polluted
4	124.94	VI	Heavily polluted
5	135.64	VII	Severely polluted
6	253.90	VII	Severely polluted
7	340.45	VII	Severely polluted
8	135.92	VII	Severely polluted
9	160.96	V	Polluted
10	56.97	VII	Severely polluted
11	117.49	VI	Heavily polluted
12	130.64	VI	Heavily polluted
13	89.33	V	Polluted

Groundwater quality map

The groundwater quality map of the study area represents the influence area delineation of various status categories of groundwater, viz. very poor, poor, good and very good. The status categories are standardized with the numerical values 1, 2, 3 and 4, respectively (Sarkar 2003). This layer is generated by plotting the network stations of groundwater with the value assigned for the status and digitized as a point layer and rasterized in the SPANS Topographer software. This function generates output in the quadtree data format. The map generated indicates very poor status of groundwater in the northern part of the coalfield and very good status of groundwater in the southern part (Fig. 9).

Surface water quality map

This map delineates areas with four status categories of surface water such as very poor, poor, good and very good. These categories of water have also been assigned a value of 1, 2, 3 and 4, respectively. The sample network stations with the status value are digitized as a point layer and rasterized in the SPANS Topographer software. The surface water quality map indicates very poor surface water over the entire study area whereas a few areas in the northeastern part are with very good surface water (Fig. 10).

Mine water quality map

The mine water quality map delineates areas with four status categories of mine water. The sample network

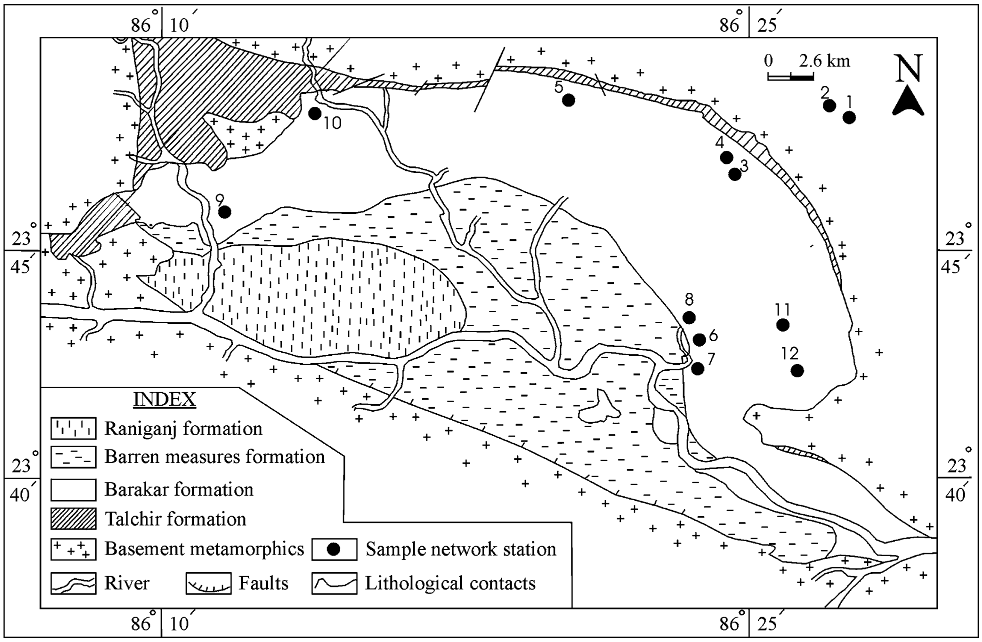

Fig. 8 Geological map of Jharia coalfield with air sample network stations

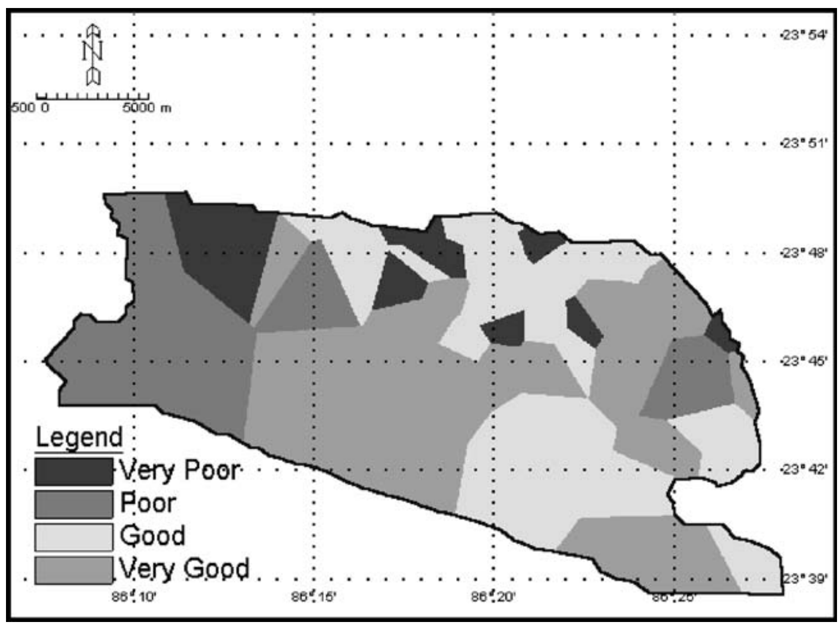

Fig. 9 Groundwater quality map of Jharia coalfield

stations were digitized as a point layer with the status value ranging from 1 to 4 and were rasterized in the SPANS Topographer software. Most of the mine water in the southern part is of poor quality whereas a few areas in the northeastern part of the coalfield are of very poor quality. There are some pockets of very good mine water in the northern part while remaining areas are with good mine water quality (Fig. 11).

Air quality map

This map represents the air quality variation throughout the coalfield. The status categories of air such as severely polluted, highly polluted and polluted were given a value of 1, 2, and 3, respectively, as there is no location with clean air in the study area. The sample network stations with these status values were digitized as point layer

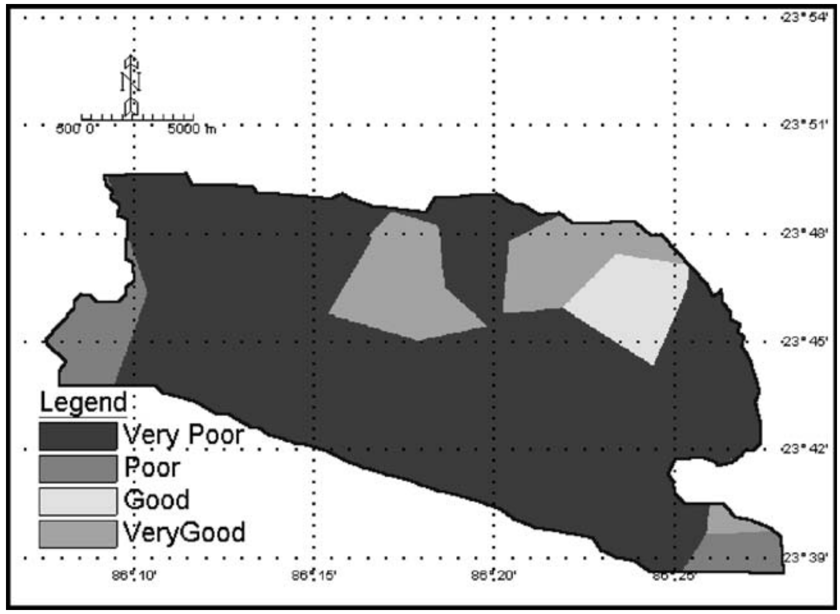

Fig. 10 Surface water quality map of Jharia coalfield

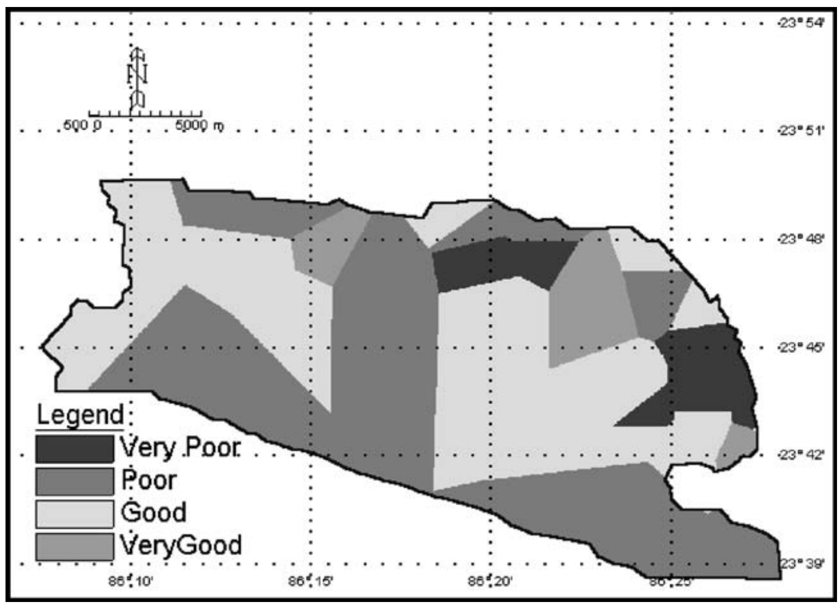

Fig. 11 Mine water quality map of Jharia coalfield

rasterized in the SPANS Topographer software. This map suggests severely polluted air in the northern part, polluted air in the southern part and heavily polluted air in the southeastern part of the coalfield (Fig. 12).

Population density map

The population density map of the study area represents the delineation of villages with various categories of population density, viz. very low, low, moderate, high and very high. The population density ranges with density class are shown in Table 19. The village boundaries with respective population density values are digitized as polygon layer and rasterized in the SPANS Topographer software. This density map suggests that the villages Godhur, Bhatdih, Kenduadih and Amlabad are with very high population density, village Loyabad with moderate density, village Putki with low density and remaining villages with very low population density (Fig. 13).

Overlay analysis

In the present study, the choice among a set of environmental impact zones is based upon multiple criteria

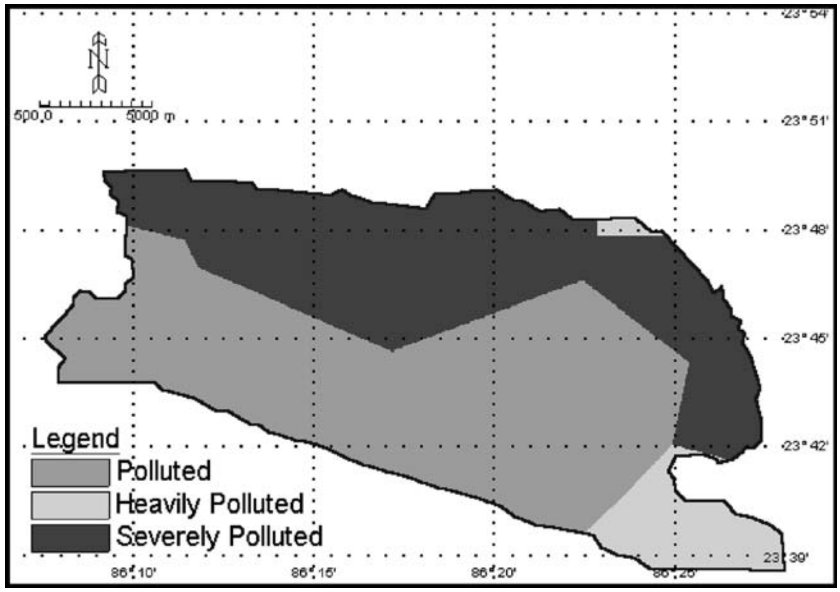

Fig. 12 Air quality map of Jharia coalfield

Table 19 Population density classification

Population density	Class
< 100	Very low density
101–250	Low density
251–500	Moderate density
501–1,000	High density
> 1,000	Very high density

such as groundwater quality, surface water quality, mine water quality, air quality and population density of villages. This process is commonly known as MCE (Sarkar et al. 2001). For multi-criteria modelling, first, identifying the quadtrees used in the analysis creates a template. Then, a matrix is created using the parameters to be overlaid. If a base map has been assigned to the study area, this function will confine the analysis to the data falling within the basemap.

Overlay analysis of water quality

The water quality of the study area is influenced by groundwater, surface water and mine water. To represent the overall water quality of the area the three types

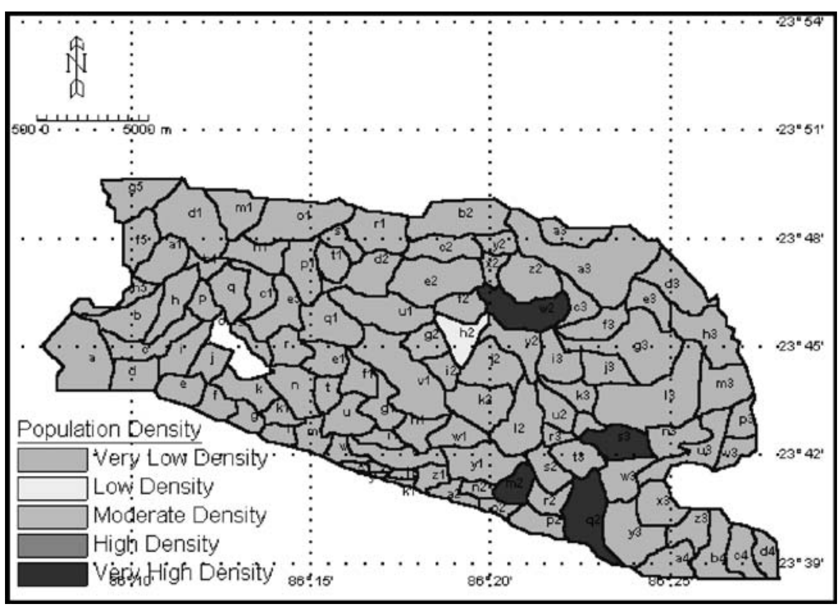

Fig. 13 Population density map of Jharia coalfield

of water, viz. ground water, surface water and mine water are overlaid using the multi-criteria modelling. First, a matrix has been generated for the suitability mapping of water quality using the status category values as shown in Table 20.

The water quality map suggests very good water in the northeastern part, very poor water in a few areas in the northern part and eastern part, good water in the central part and poor water in the southern part of the study area (Fig. 14).

Overlay analysis of water and air qualities

This analysis has been carried out to delineate areas influenced by integrated effect of air quality and water quality. For this analysis, a matrix has been created using the air quality and water quality status categories (Table 21).

As there is no sample location with clean air, the very good status category is not taken into consideration. This analysis between air and water qualities suggests that most of the areas are influenced by integrated poor air and water qualities. In the south central part, a few areas are with good environment and a few areas with very poor quality of environment in terms of air and water qualities (Fig. 15).

Table 20 Status category for overlay analysis of water quality

	Very poor	Poor	Good	Very good
Groundwater	1	2	3	4
Surface water	1	2	3	4
Mine water	1	2	3	4

Environmental impact zonation

Environmental impact zonation map delineates areas into different environmental impact zones such as high impact, moderate impact and low impact zones. A matrix has been generated for this analysis using the parameters of air quality, water quality and population density (Table 22). Air quality indices of all individual sampling stations yielded either 'polluted', 'severely polluted' or 'heavily polluted' status class. The influence zones of the air sampling points when overlaid with water quality indices yielded no status category as 'very good'.

Population density has also been taken as a parameter because the population of the area also has impacts on the total geo-environment. This final output in terms of environmental impact zonation map suggests that most of the areas of the coalfield fall in the moderate impact zone. Some of the villages in the southern and south central part of the area fall in the high impact zone and a few villages in the central part of the coalfield fall in the low impact zone (Fig. 16).

Results and discussions

Unplanned spurt in human activities due to mining affect the geo-environment of the mining areas. While carrying out developmental activities, the assimilative capacities of the geo-environmental components, i.e. air,

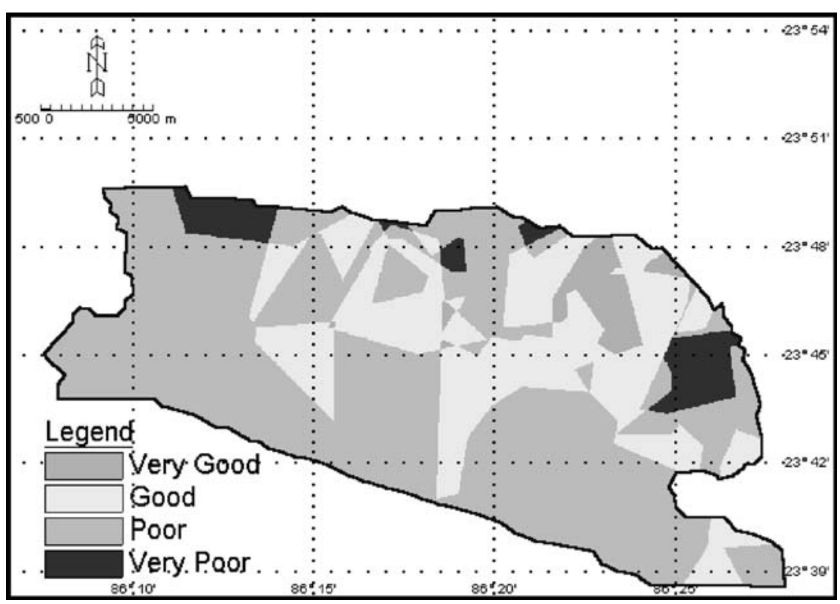

Fig. 14 Overall water quality map of Jharia coalfield

Table 21 Status categories for overlay analysis of water and air qualities

Air	Water			
	Very poor	Poor	Good	Very good
Polluted	1	2	3	3
Heavily polluted	1	2	2	2
Severely polluted	1	2	2	2

Table 22 Status categories for environmental impact zonation

Environment	Population density				
	Very low	Low	Moderate	High	Very high
Very poor	2	1	1	1	1
Poor	2	2	1	1	1
Good	3	3	2	1	1

water and land, to pollution should also be paid due weightage. A geo-environmental development program needs a large volume of multidisciplinary data from various sources. In Jharia coalfield, unplanned mining history prior to 1970 and urban sprawl resulted in damage to the quality of water and air (Ghosh and Ghosh 1991). In the present study, geo-environmental components, i.e. water and air qualities, of Jharia coalfield have been evaluated and assessed. Multivariate statistical studies have been carried out for groundwater, surface water and mine water of the area. In the case of groundwater, basically two main interrelated types of chemical constituents are responsible for the hydrogeochemical variability in the study area. Based on the dendrogram, the study area has been inferred to constitute two types of groundwater. Cluster analysis for surface water of the study area indicates two broad types of surface water, viz. EC type and iron type. The EC type water includes two subtypes. The dendrogram obtained from cluster analysis reveals two distinct *types* of mine water in the study area.

While WQI calculated for groundwater revealed good to very good quality index, that calculated for suitability of surface water and mine water for human consumption indicates poor to very poor status of water for drinking purpose. Air quality index is calculated to classify the air quality of the study area into different status categories, viz. very clean, clean, fairly clean, moderately polluted, polluted, heavily polluted and severely polluted. There is no sample station with clean air quality, which indicates the hazardous degradation of air environment in the study area.

The thematic information layers generated in GIS provide spatial distribution of various status categories of water and air in the study area. To generate the water quality map, first the groundwater quality, surface water quality and mine water quality maps are generated and overlaid using MCE. The water quality map suggests that in most areas the water is of poor quality. Few areas in the northeastern part of the coalfield are having very good quality water whereas the central part of the coalfield has good quality water. In the eastern and northwestern part of the coalfield, there are a few areas with very poor quality water.

The air quality map suggests that the southern part of the coalfield is covered by polluted air, whereas the air in the northern part of the coalfield is severely polluted. Air

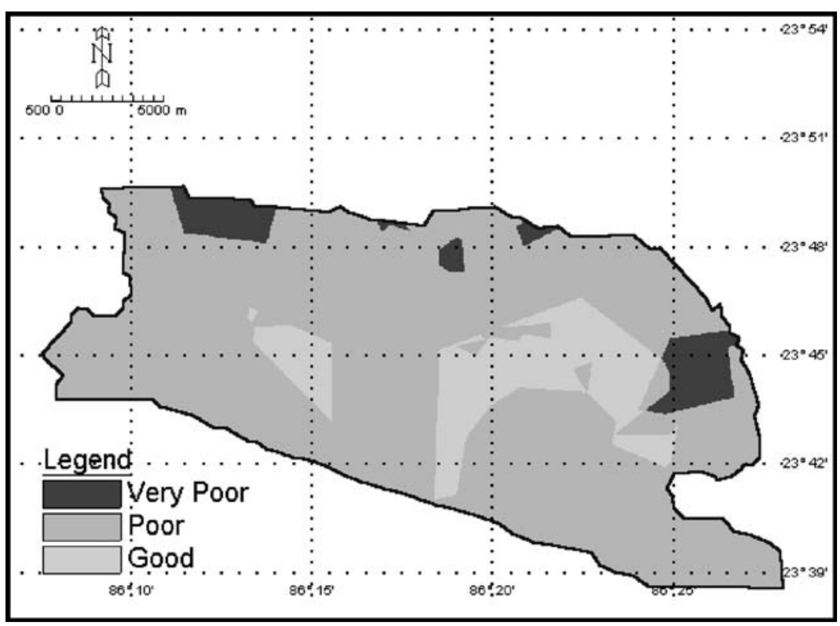

Fig. 15 Combined water and air quality map of Jharia coalfield

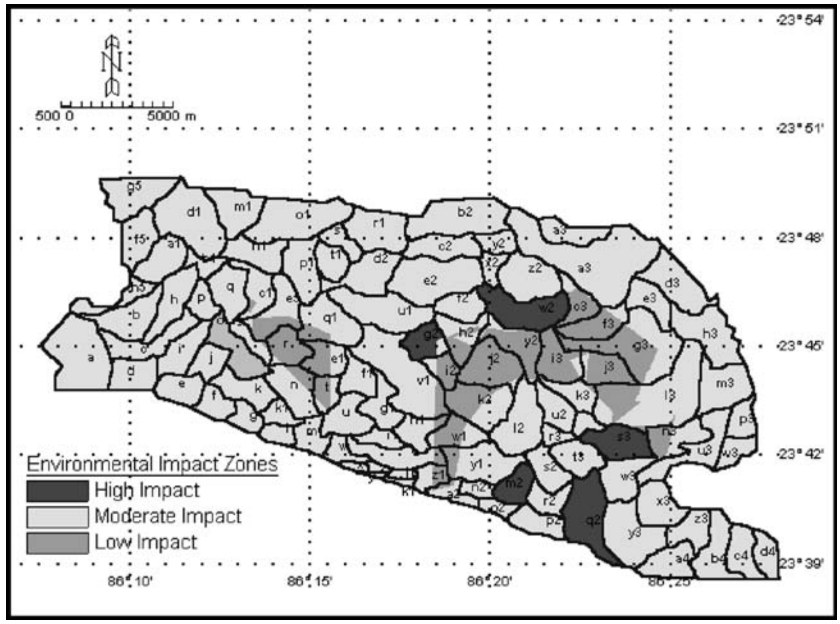

Fig. 16 Environmental impact zonation map of Jharia coalfield

in the southeastern part of the coalfield is heavily polluted. Matrix analysis between air and water qualities has been carried out to delineate areas with combined influence of various status categories of water and air qualities. This analysis shows that most of the areas in the coalfield are in poor condition if the two variables, air and water, are considered together. A few areas in the central Jharia coalfield are of good condition while some parts in northwestern and eastern part are of very poor condition.

Identification of highly stressed villages in terms of QoL as per the evaluation of geo-environmental quality assessment plan has been carried out using the MCE. Integrated air and water quality has been overlaid on population density map of the coalfield to delineate villages with high impact, moderate impact or low impact of environmental degradation. Villages namely Loyabad, Godhur, Kenduadih, Amlabad and Bhatdih have been determined to be highly stressed, villages namely Jirampur, Ghanuadih, Kendidih, Fatepur, Bharakuta, Bagdigi, Chotakakirabad, Aralgoria, Putki, Sealgudri, Sohnidih, Tundi, Gobindpur are low stressed while remaining villages are moderately stressed.

Maximum areal extent of the coalfield thus falls in the moderate environmental impact zone, which indicates the degradation of geo-environment in the study area. To maintain the ecologically sustainable industrial development, an attempt has to be made to take suitable measures to overcome hazards associated with appropriate development of the area.

Acknowledgments The authors are thankful to Bharat Coking Coal Limited, Dhanbad, and Centre of Mining Environment, Indian School of Mines, Dhanbad, for their data support and infrastructure facilities extended to the first author. Thanks are due to the Department of Applied Geology, Indian School of Mines, Dhanbad, for use of computational facilities in its GIS and Geostatistics laboratory.

References

Chadwick MJ, Highton NH, Lindman N (1987) Environmental impacts of coal mining and utilisation. Pergamon Press, UK, pp 73–80

Chandra D (1992) Jharia coalfield. Geological Society of India, Bangalore, pp 1–11

Davis JC (1973) Statistics and data analysis in geology. Wiley, New York, pp 456–467

Davis JC (1986) Statistics and data analysis in geology, 2nd edn. Wiley, New York, pp 502–514

Frangi JP (1996) Spatio-temporal mapping of the NO_x concentration over the Paris Area. C R Acad Sci Paris T-323, Series IIa, 373–379

Ghosh R, Ghosh DN (1991) Impact assessment of mining in an area with a long diverse mining history—a case of a coalfield in India. Inst Eng (I) Min 72:29–32

Gogoi R (1999) Air quality assessment and its impact on the community of a mining complex. M. Tech, Indian School of Mines

Hinawi EE (1981) The environmental impacts of production and energy. Tycooly Press, Dublin, pp 57–59

ISI (1975) Indian standard method for measurement of air quality, IS: 1582 (Part VI)

Karunakaram C (1982) Role of environmental geology in environmental planning for mining operations. In: Proceedings of national seminar on minerals and ecology, Delhi, 16–18 February 1982
Koch GS, Link RF Jr (1970) Statistical analysis of geological data, vol 1. Wiley, New York, pp 330–333
Krishnamurthy KV (2004) Environmental impacts of coal mining in India. J Inst Public Health Eng India:1–9, spl edition (NSEEME-2004)
Kumar C (2002) Hydrogeological framework of the drought prone upper catchment of Gandheswari micro-watershed Bankura district, West Bengal. M. Sc. Tech, Indian School of Mines
Mahanta BN, Sarkar BC, Singh G, Saikia K, Paul PR (2004) Multivariate statistical modeling and water quality indexing in and around Jharia coalfield, Jharkhand. J Inst Public Health Eng:215–228, spl edition (NSEEME-2004)
Miller RL, Kahn JS (1962) Statistical analysis in the geological sciences. Wiley, New York, pp 259–299
Mishra PC, Patel RK (2001) Study of the pollution load in the drinking water of Rairangpur—a small tribal dominated town of north Orissa. Indian J Environ Ecoplan 5(2):293–298
Naik S, Purohit KM (2001) Studies on water quality of river Brahmani in Sundargarh district, Orissa. Indian J Environ Ecoplan 5(2):397–402
Parks JM (1966) Cluster analysis applied to multivariate geological problems. J Geol 74:703–715
Rao NS (1997) Studies on water quality index in hard rock terrain of Guntur district, Andhra Pradesh, India. In: Proceedings of national seminar on hydrogeology of Precambrian terrains and hard rocks areas, Dharwad, pp 129–134
Rao SVL (2003) Cluster analysis of groundwater quality data of Venkatagiri Taluq, Nellore district, Andhra Pradesh. J Geol Soc India 62:447–454
Rao NS, Rao JP, Devadas DJ, Rao KVS (2002) Hydrogeochemistry and groundwater quality in a developing urban environment of a semi-arid region. Guntur, Andhra Pradesh. J Geol Soc India 59:159–166
Sarkar BC (2003) Geographic information system and its role in geo-environmental issues. ENVIS monograph No. 10. ENVIS Center of Mining and Environment, Center of Mining Environment, ISM, Dhanbad, pp 1–143
Sarkar BC, Deota BS, Raju PLN, Jugran DK (2001) A geographic information system approach to groundwater potentiality of Shamri microwatershed in the Shimla taluk, Himachal Pradesh. J ISRS Photonirvachak 29(3):151–164
Till R (1974) Statistical methods for the earth scientists: an introduction. Macmillan, London, pp 141–142
Voogd H (1983) Multicriteria evaluation for urban and regional planning. Princeton University Press, London