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ORIGINAL PAPER

Evaluation of aquifer vulnerability in a coal mining of India by using GIS-based DRASTIC model

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Abstract The objective of this study is to estimate the aquifer vulnerability in the West Bokaro coalfield, Jharkhand, India, by using a geographic information system (GIS)-based DRASTIC model. The DRASTIC model incorporates seven hydrogeological data, i.e. depth of water table, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity. The model was validated by comparing the model output (vulnerability index map) with a statistical analysis and the actual SO_4^{2-} and Fe concentrations in the groundwater of the study area. Thirty-three well samples were collected from the West Bokaro coalfield area. These were analyzed in the laboratory to measure the level of SO_4^{2-} and Fe in the groundwater. The GIS-based DRASTIC result showed that 0.06 % of the area fell into the low-vulnerability zone and 10.8 % fell into the moderate vulnerability zone. About 87.7 % of the study area fell into the moderate to high-vulnerability zone, and 1.4 % of the study area was classified as the highly vulnerable zone. From the vulnerability map, it was observed that some of the western part and some of the middle part of the study area lay in the high-vulnerability zone, and therefore, they were more susceptible to aquifer pollution. The geogenic and anthropogenic activities are responsible for the high vulnerability in the study area. The shallow water level, topography, high net recharge and permeable vadose zone of the area served as the major influential parameters in mapping the vulnerability. The mining and related activities are also responsible for the high aquifer vulnerability of the area. The aquifer vulnerability maps generated in this study could also be used for the management of future water resources and environmental planning in all the mining regions.

Keywords West Bokaro coalfield · Groundwater · Vulnerability mapping · Validation · Impact of geogenic and mining activities

Introduction

Assessment of aquifer vulnerability can define areas that are contaminated by anthropogenic activities or natural activities. Vulnerability refers to the sensitivity of the groundwater to contamination and is determined by intrinsic characteristics of the aquifer. Aquifer vulnerability is a significant approach for the assumption that the physical environment may provide some degree of protection for groundwater against human and natural impacts, particularly with respect to pollutants entering the subsurface environment. The concept of vulnerability was first introduced in France in the 1960s for the assessment of the groundwater for contamination (Margat 1968; Albinet and Margat 1970). Groundwater vulnerability is also defined as the propensity and possibility for common contaminants to reach the water table after introduction at the ground surface level (Sniffer 2004). However, vulnerability assessment is essential for strategies to protect groundwater and land use (Foster 1988).

Mining threatens the quality and quantity of surface and groundwater resources in many parts of the world (Tiwary 2001; Olıas et al. 2004; Neves and Matias 2008; Singh et al. 2008, 2010; Bhuiyan et al. 2010). Most mines in India do not

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practice water management; contaminated mine water is commonly discharged into open channels without any treatment or beneficial use. Moreover, mining and related activities can damage the aquifer and reduce available groundwater supplies. The population in the West Bokaro coalfield area very much depends on the groundwater for drinking and domestic purposes.

Groundwater vulnerability maps are commonly used to identify the area at maximum risk of groundwater contamination on the basis of anthropogenic and geogenic factors (National Academy of Sciences 1993). Groundwater vulnerability mapping is a vital tool for visualizing the sensitivity of groundwater resources in their environment and is thus useful for decision making, planning and law application (Rahman 2008; Farjad et al. 2012). Spatial analysis techniques can help to estimate, evaluate and manage the groundwater vulnerability assessment. In Germany, Vierhuff and Aust (1981) made a vulnerability map of the former Federal Republic of Germany before reunification on the same scale. The recent international practices in the mapping of groundwater vulnerability have been reviewed by Vrba and Zaporozec (1994); Magiera (2000); Al Zebet (2002) and others. For the assessment of intrinsic vulnerability, several researchers have developed many methods like GOD (Foster 1987), DRASTIC (Aller et al. 1987), SINTACS (Civita and De Maio 1997), EPIK (Doerfliger and Zwahlen 1998), PI (Goldscheider et al. 2000) and COP, based on the European approach (COST 65 1995). The DRASTIC model has been developed using four major assumptions: (a) the contaminant is introduced at the ground surface, (b) the contaminant is flushed into the groundwater by precipitation, (c) the contaminant has the mobility of water, and (d) the area evaluated using DRASTIC is 100 acres/0.4 km^2 or larger (Aller et al. 1987; Al Zebet 2002). We have selected the DRASTIC method for assessment of the aquifer vulnerability in a coalfield area of India.

The geographic information system (GIS) has become one of the most prominent tools in the field of hydrological science that help to plan for the convention of water resources of any area. GIS has been widely used for the management of environmental problems (Panagopoulos et al. 2012; Papadopoulou-Vrynioti et al. 2013; Shirazi et al. 2013; Papadopoulou-Vrynioti et al. 2014; Ghosh et al. 2015). Many countries have used a GIS-based DRASTIC model for the assessment of groundwater vulnerability such as Tunisia, Nepal, China, Iran, Japan, Turkey, Malaysia, USA, Algeria, Nigeria and others (Nasri et al. 2014; Pathak et al. 2009; Kabera and Zhaohui 2008; Chitsazan and Akhtari 2009; Babiker et al. 2005; Sener et al. 2009; Shirazi et al. 2013; Fritch et al. 2000; Samey and Gang 2008; Edet 2014). In India, several researchers have also used a GIS-based DRASTIC model for the evaluation of the groundwater vulnerability (Jha and Sebastian 2005; Ckakraborty et al. 2007; Rahman 2008; Umar et al. 2009; Prasad et al. 2011; Saha and Alam 2014; Krishna et al. 2014; Ghosh et al. 2015). However, perhaps, this is the first study which uses a GIS-based DRASTIC model to assess the aquifer vulnerability of a coalfield region in India. The study is particularly important due to the declining quality of the groundwater in the coalfield areas of India.

In the present study, a GIS-based DRASTIC model was used to map the aquifer vulnerability and detect the areas of high vulnerability. This study aims to provide an in-depth understanding of the aquifer system, hydrogeological setting and impact of mining on groundwater in the area for the development and safe exploitation of the groundwater resources. The present baseline information will be very useful for the management of future groundwater resources in these mining regions.

Materials and methods

Site description

The study area is the West Bokaro coalfield region, covering an area of 207 km^2 and located in the Ramgarh district, Jharkhand, India. The West Bokaro coalfield stretches between 23°41′ to 23° 52′ N latitude and 85° 24′ to 85° 41′ E longitude, as shown in Fig. 1. It spreads 65 km from east to west and 10 to 16 km from north to south. Bokaro West and Bokaro East are two subdivisions of the field separated almost in the middle by Lugu Hill (height 960.9 m), which has an area of about 25 km^2. The West Bokaro coalfield is drained by the Bokaro River passing through the central part of the coalfield with an easterly flow. The Bokaro River rises on the Hazaribagh plateau, south of Hazaribagh, but quickly skirts the southern face to pass through a narrow and beautiful valley between the Jilinga and Langu Hills. It subsequently passes through the West Bokaro and East Bokaro coalfields. The Bokaro River flows into the Konar River shortly before the latter flows into the Damodar River. The Chautha River and Chotha River are the main tributaries of the Bokaro River which drains the northern hilly terrain and southern region of the coalfield.

Climate and rainfall

The West Bokaro coalfield area has a tropical climate and is characterized by a very hot pre-monsoon and cold post-monsoon season. The period from May to mid-June is the peak of the pre-monsoon season, with an average maximum temperature of 44 °C. The summer is very hot and dusty, but nights are generally pleasant. The winter (November to February) is cold, and the minimum temperature is 4 °C. In the area, the rainfall mostly occurs in the monsoon period, June to September. Meagre rainfall due to conventional

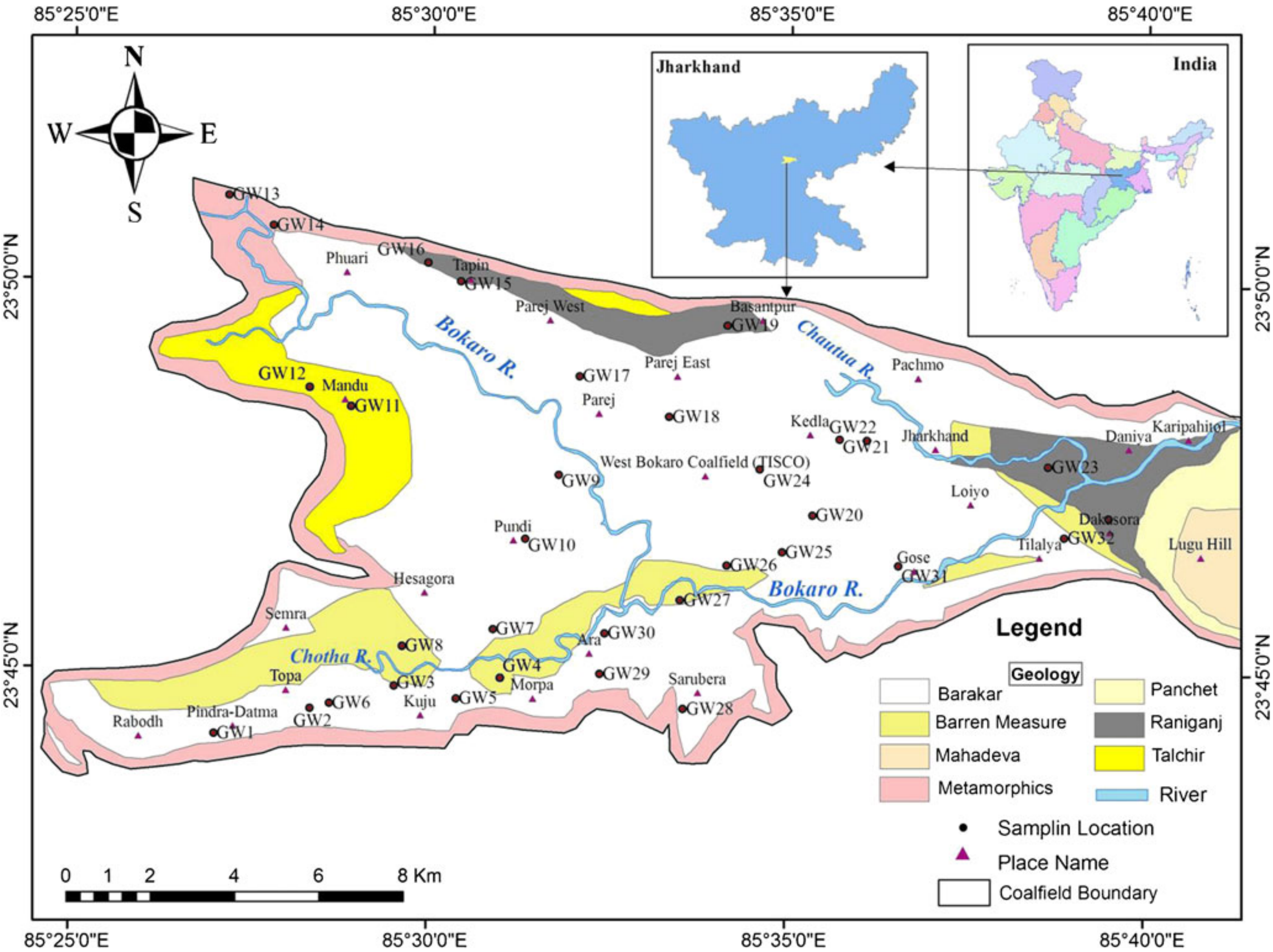


Fig. 1 Well inventory locations and geological map of the West Bokaro coalfield

thunderstorms occurs during the months of April and May (http://ietd.inflibnet.ac.in:8080/jspui/bitstream/10603/16830/9/09_chapter%202.pdf). The winter rainfall occasionally occurs due to western disturbances. The variability of rainfall has a recorded maximum during the months of July and August. It is observed that the average annual rainfall fluctuates in a range between 927 and1588 mm. The average annual rainfall is 1418 mm, and more than 85 % of annual rainfall occurs during the four monsoon months, June to September (Mondal et al. 2009; Tiwari et al. 2016a).

Geology

The West Bokaro coalfield is broadly divided into two sub-basins: the Northern Sub-basin and the Southern Sub-basin divided by the Archean highland around Mandu. The West Bokaro coalfield forms a broad syncline with its axis trending E-W, and it exhibits a completed sequence of lower Gondwana Formation, which rests unconformably on basement rocks. The geology of the study area consists of the Barakar Formation, Barren Measures, Mahadeva, Metamorphics, Panchet, Raniganj and Talchir Formation (Fig. 1). The Barakar Formation covers the majority of the coalfield and is composed of coarse- to fine-grained sand stone, pebbly conglomerates, gritty sandstones, grey shales, carbonaceous shales, fire clays and coal seams (Table 1). The coalfield exhibits a twin synformal structure, known as northern and southern synform, separated by a hill which represents a complementary central antiform in an E-W direction. In the northern limbs of the northern synform, the beds generally dip towards south, varying from 15° to 25°. The dips in the southern limb of this synform are 5° to 15° towards north except the sub-basinal structures, as in the Tapin and Parej blocks. The coalfield is traversed by numerous strike and oblique faults. The throw of these faults varies from a few meters to more than 400 m. Igneous rocks intrusive in the form of mica-peridotite, lamprophyre and dolerite are seen in the coalfield. Dolerite dykes are exposed near the Tapin, Kedla-Jharkhand and Choritand-Tilaiya blocks trending more or less in NE-SW direction.

Table 1 Stratigraphy of the West Bokaro coalfield

Formation	Lithology	Period
Detrital mantle	Soil and sub-soil	Recent
Basic intrusives	Dolerites, lamprophyres and mica peridotites	Jurassic and Post Jurassic
Raniganj Formation	Fine- to medium-grained greyish green , white to buff coloured, highly current bedded sandstones, grey shales with thin uneconomic coal seams	Permian
Barren Measures Formation	Carbonaceous and micaceous shales, with siderite lenses and alternating compact ferruginous sandstones, shales with thin coal bands	Permian
Barakar Formation	Coarse- to fine-grained sand stone, pebbly conglomerates, gritty sandstones, grey shales, carbonaceous shales, fire clays and coal seams	Permian
Panchet Formation	Medium to coarse brown sandstone, shales and red clays	Permian
Talchir Formation	Dark to light greyish green sandstone and shales	Permo-Carboniferous
——Unconformity——		
Metamorphics	Porphyritic and granitoid biotite gneisses and others	Pre-Cambrian

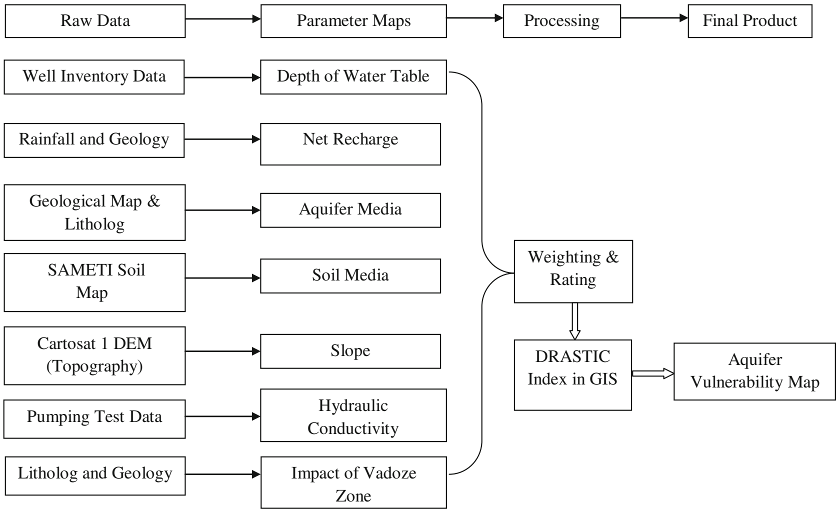
Hydrology and hydrogeology

The environmental setting and topography of the area are generally sloping towards east to southeast. The entire coalfield is drained by the upper reaches of the Bokaro River. There are no other important rivers in the area. There are small seasonal streams scattered over the entire region. In the northern part of the area, there is a small river which flows west to east and is non-perennial. These small rivers act as a drain for the mine effluents and ultimately join the Bokaro River. The entire area under the Ramgarh district of the Jharkhand state comes under a part of the Chotanagapur plateau, and the area is characterized by Archaean metamorphics and coal bearing lower Gondwana sedimentaries with a thin cover of alluvium and laterite soils. Groundwater in the area occurs under water table conditions in the weathered mantle of diverse rock units and along planes of structural weakness. In general, the water-level depth in the area ranges between 0.82 and 46.6 ft from the ground level. There are mainly three types of rocks present, namely Gondwanas, schists and granites.

The DRASTIC model

The DRASTIC model was developed in the USA by the Environmental Protection Agency in 1987 to evaluate the potential for groundwater contamination (Aller et al. 1987). The DRASTIC was used to assess the comparative vulnerability of areas to groundwater contamination by focusing on hydrogeologic factors that influence pollution potential (Aller et al. 1987). This method is based on hydrogeological parameters which govern the occurrence and movement of the groundwater into the system. The DRASTIC model considers seven parameters which, taken together, provide the acronym. These are Depth to groundwater, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and Hydraulic Conductivity (Fig. 2). These seven parameters are

Fig. 2 Methodology flowchart



pooled in a simple linear equation after they have been standardized from the physical range scale to a 1- to 10-grade relative scale. Each parameter is multiplied by a weighting coefficient as given in Table 2. In this system, the degree of

Table 2 Weight, ranges and ratings of the seven DRASTIC parameters

Parameter	Data sources	Class	Rating	Weight
Depth-to-water table (ft)	Well inventory	0–5	10	5
		5–10	9	
		10–20	8	
		20–30	7	
		30–50	5	
		50–75	3	
		75–100	2	
		100+	1	
Net recharge (in/year)	Rainfall and hydrogeology	0–2	1	4
		2–3	2	
		3–6	5	
		6–8	7	
		8+	9	
Aquifer media	Lithology	Massive shale	2	3
		Metamorphic/igneous	3	
		Weather metamorphic/igneous	4	
		Glacial till	5	
		Bedded sandstone, shale sequences, massive sandstone, massive limestone	6	
		Sand and gravel	8	
		Basalt	9	
		Karst limestone	10	
Soil media	Soil map	Thin or absent/gravel	10	2
		Sand	9	
		Shrinking/aggregating clay	7	
		Sandy loam	6	
		Loam	5	
		Silty loam	4	
		Clay loam	3	
		Non-shrinking/non-aggregating clay	1	
Topography (% slope)	Cartosat 1 DEM	0–2	10	1
		2–6	9	
		6–12	5	
		12–18	3	
		18+	1	
Impact of vadose zone media	Lithology	Silt/clay	1	5
		Shale	3	
		Granite/gneiss	4	
		Sandstone/large limestone formation	6	
		Basalt	9	
		Small limestone formation	10	
Hydraulic conductivity (GPD/ft^2)	Pumping test data	1–100	1	3
		100–300	2	
		300–700	4	
		700–1000	6	
		1000–2000	8	
		2000 +	10	

Source: Aller et al. (1987)

vulnerability to pollution in the groundwater is based on the numerical index value. These index numbers are derived from the rating and weights assigned to every thematic layer.

The equation for determining the DRASTIC Index (DI) is as follows:

$$Di = \mathrm{Dr} \times \mathrm{Dw} + \mathrm{Rr} \times \mathrm{Rw} + \mathrm{Ar} \times \mathrm{Aw} + \mathrm{Sr} \times \mathrm{Sw} + \mathrm{Tr} \times \mathrm{Tw} + \mathrm{Ir} \times \mathrm{Iw} + \mathrm{Cr} \times \mathrm{Cw}$$

where D = depth to groundwater, R = recharge, A = aquifer media, S = soil media, T = topography, I = impact of the vadose zone, C = hydraulic conductivity, r = rating and w = weighting.

In the study area, 33 well monitoring locations have been selected for monitoring the water level in the West Bokaro coalfield area. The depth-to-water level has been recorded using a sensor-based water-level recorder for the post-monsoon period 2012. Secondary data such as toposheets were obtained from the Survey of India Kolkata, the soil map from the State Agriculture Management and Extension Training Institute (SAMETI), the geological map collected from the Geological Survey of India and Coal Atlas. The vadose zone and hydraulic conductivity data were collected from the litholog of different mines of Central Coalfield Limited (CCL), India. Rainfall data was taken from the weather station located at the Kuju area office of the West Bokaro coalfield. Digital elevation model (DEM) of 30-m resolution was procured from the BHUVAN portal of National Remote Sensing Centre (NRSC). For the spatial distribution map, first, the corresponding toposheets are geo-referenced to the projection UTM datum: WGS 84 and zone 45 N in GIS 10.2 environment. These toposheets were digitized in GIS platform to generate the base map of the West Bokaro coalfield. The collected soil and geological map were scanned and digitized in Arc GIS 10.2. The DEM data transformed into GIS database has been used to generate the slope map of the study area. The DRASTIC parameter maps were generated from the raw data sources in GIS 10.2 environment (Fig. 2).

Results and discussion

Depth-to-water table (*D*)

The depth to water table is important, for the determination of how much time a contaminant travels before reaching the aquifer. In general, there is more possibility for dilution to occur as depth to water increases, thereby permitting longer travel times (Aller et al. 1987). In this study, water-level depths of 33 observation wells have been taken by covering one monsoon cycle from November 2012. The maximum and minimum water-level depths are 35.17 and 0.98 ft below ground level (ftbgl), respectively. The average water level is 9.75 ftbgl. These point data were contoured by interpolating and divided into five categories, i.e. 0–5, 5–10, 10–20, 20–30 and 30–50 ft, and assigned the variable ratings of 10, 9, 8, 7 and 5 according to DRASTIC rating. Thereafter, these ratings were converted into grid to make raster data for use with GIS

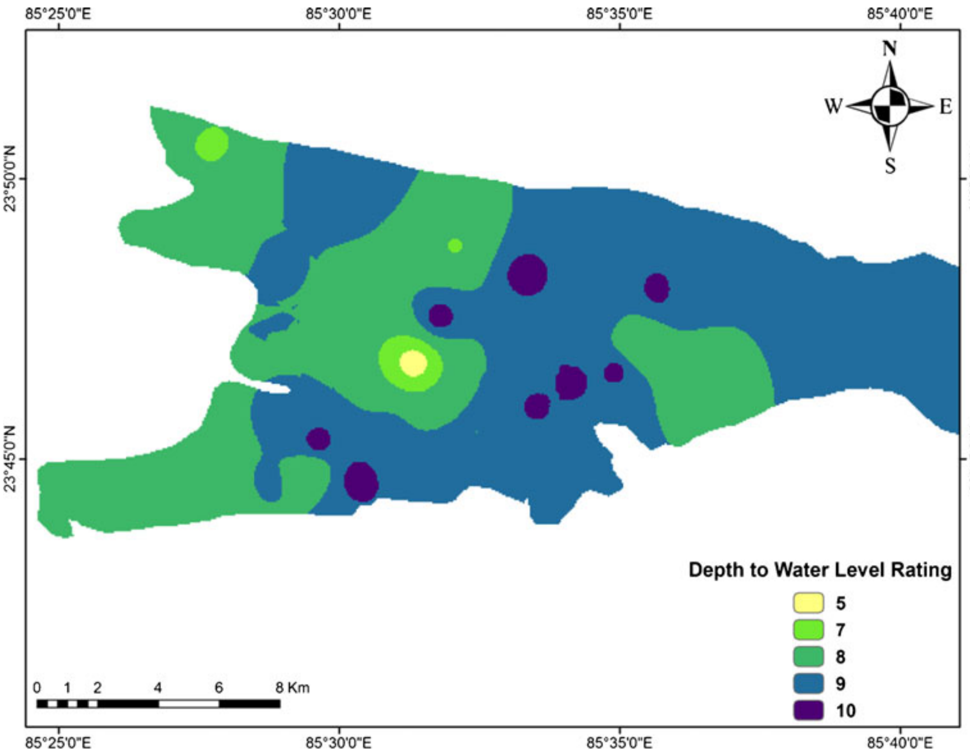


Fig 3 Depth-to-water table rating map of the study area

operation. The depth-to-water table interval range, DRASTIC rating, weight and resulting index are portrayed in Fig. 3. Areas with shallow water tables are vulnerable because pollutants have short distances to travel up to the groundwater. So, the deeper the groundwater level, the lower the vulnerability and smaller the rating value. The water level is deeper in the middle and northeastern part of the study area, whereas it is shallow in the west and southern part.

Net recharge (*R*)

Net recharge shows the volume of water per unit area of the land, which penetrates the ground surface and enhances the water table. The more recharged water that leaks through, the greater possibility for the recharge to carry pollution into the aquifer (Aller et al. 1987). The primary source of the groundwater recharge in the study area is rainfall. However, the West Bokaro coalfield area is also recharged by the rivers and mine pump water that contributes more to the groundwater pollution because coal mining and its related activities can lead to groundwater pollution. Coal mines are a major source of metal contaminants (Bhuiyan et al. 2010; Mahato et al. 2014; Tiwari et al. 2016b). Net recharge of the area was calculated according to Ground Water Resource Estimation Committee (Ground Water Resource Estimation Methodology 1997, 2009). The net recharge rate varies from 2.3 to 7.0 in/year. Net recharge was divided into two categories, i.e. 2–4 and 4–7 in/year. According to the Ground Water Resource Estimation Committee (Ground Water Resource Estimation Methodology 1997, 2009), the Talchir Formation has a low recharge rate (4 %). The Metamorphic and Mahadeva Formations have a moderate recharge rate, 8 and 7 %, respectively, while the Barakar Formation, Barren Measures and Raniganj have a high recharge rate (12 %). Most of the study area is covered by the Barakar Formation, which leads to the high groundwater recharge rate and is at high risk because of the permeable pathway from the surface to the water table, while the rest of the study area is at low risk because of the low recharge rate (Fig. 4).

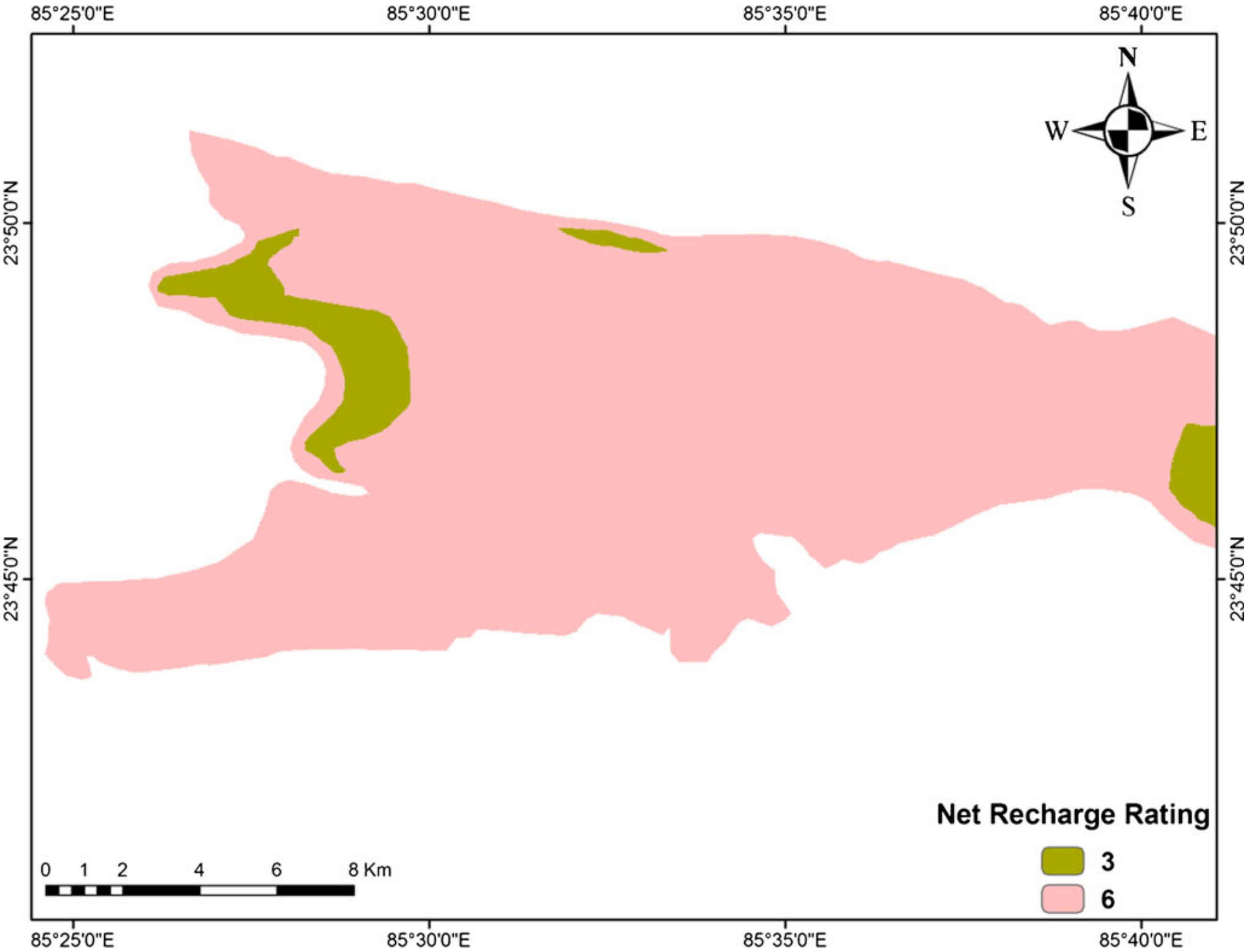


Fig. 4 Net recharge rating map of the study area

Aquifer media (*A*)

An aquifer is the saturated permeable geologic formation which holds and transmits water in gainful amounts for water supply and usually has hard rock terrain, sand and gravel. In general, the larger the grain size and greater the number of fractures or openings within the aquifer, the higher the permeability and the lower the attenuation capacity of the aquifer media (Aller et al. 1987). The media also exert a major control over the pollutant's route and path length (Saha and Alam 2014). The aquifer materials are almost coarse and medium sand stone and grit shale in most of the study area and are assigned a uniform typical rating of 6. The typical value 2 has been assigned to the aquifer media, composed of gneiss shale and fine sandstone, and the typical rating 3 has been assigned to the metamorphic aquifers (Fig. 5).

Soil media (*S*)

Soil is mostly considered the upper weathered zone (1.8 m or less) of the earth. It has a valuable effect on the quantity of recharge water which can infiltrate into the ground and hence influence the strength of a contaminant to move vertically into the vadose zone (Umar et al. 2009). There are four types of soil present in the study area, i.e. fine soil, fine loamy soil, loamy soil, and sandy loamy soil. The most of the study area (about 110 km^2) is covered by fine loamy soil, and the rest of the 58 km^2 area is covered by loamy soil. Fine and sandy loamy soil is found in a small part of the study area, which covers an area of 23 and 16 km^2, respectively. On the basis of porosity (Freeze and Cherry 1979), sandy loamy has been given the highest rating of 6, with rating 5 to the loamy and ratings 3 and 2 to fine loamy and fine soils, respectively (Fig. 6).

Topography (*T*)

Topography in the DRASTIC model refers to the slope of the land surface. Topography indicates whether a contaminant will run off or remains on the surface long enough to infiltrate into the groundwater (Aller et al. 1987). Areas with low slope tend to retain water for a longer period of time. This allows a greater infiltration or recharge of water and a greater potential for contaminant migration. Areas with steep slopes, having large amounts of runoff and smaller amounts of infiltration, are less vulnerable to groundwater contamination. Several works have been conducted in the recent years on understanding the key factors that influence the stability of slopes in the mining regions (Vishal et al. 2010; Trivedi et al. 2012; Pradhan et al. 2014). A topography map has been generated from Cartosat 1 DEM. It is described in the form of slope in the DRASTIC model, which is one of the factors controlling the infiltration of water into the subsurface, hence an indicator for the prospect of groundwater pollution. The slope of the area, as shown in Fig. 7, indicates that it varies from 0 to more than 30.1 %. The slopes have been classified into five categories, i.e. 0–2, 2–6, 6–12, 12–18 and more than 18 %. Most of the study area

Fig. 5 Aquifer media rating map of the study area

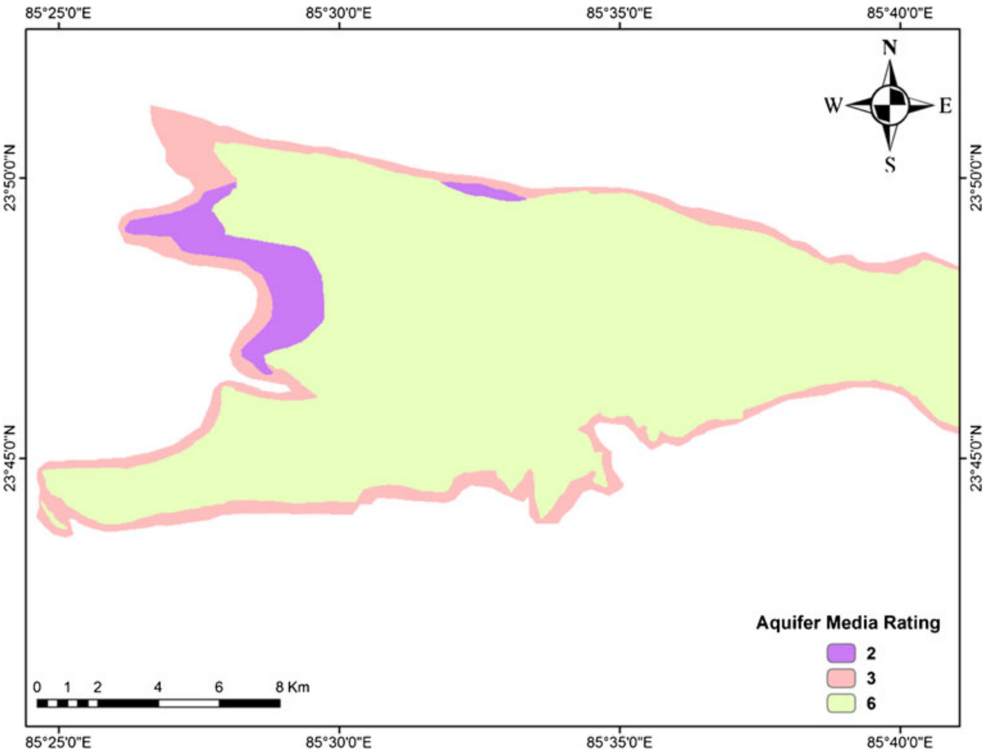
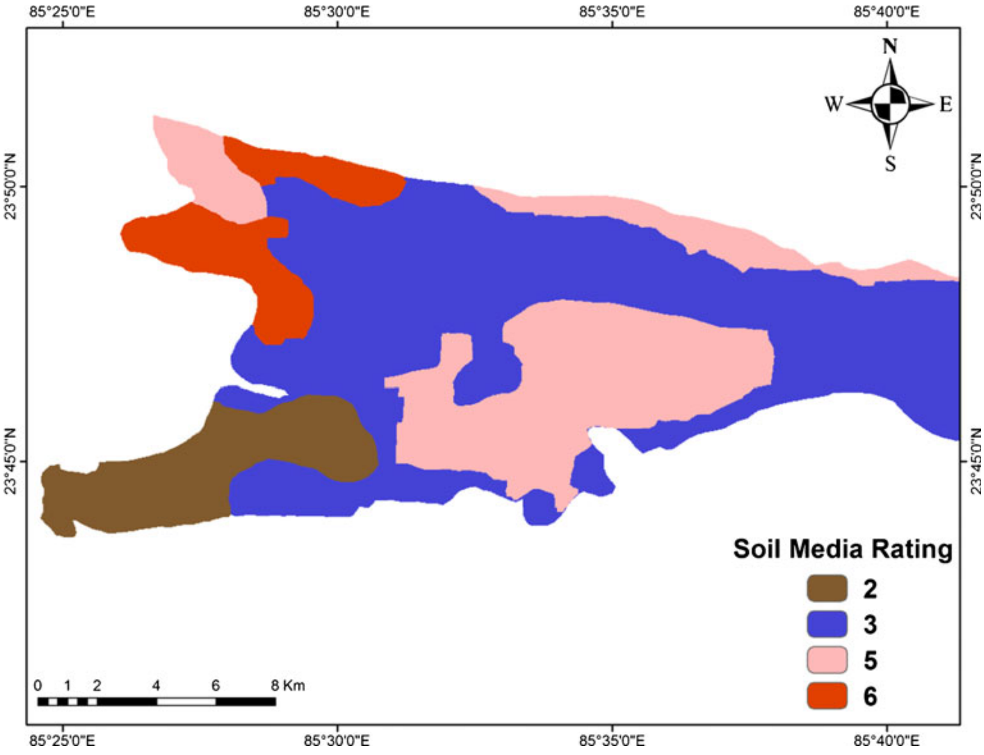


Fig. 6 Soil media rating map of the study area



occupies slope category of 2–6 and 6–12 %. In the model parameter, the slope varying from nearly level to very gentle has been assigned a maximum rating of 10, whereas the lowest value has been assigned to the very steep slope (Fig. 8).

Impact of the vadose zone media (*I*)

The vadose zone is defined as that zone above the water table which is unsaturated or discontinuously saturated, lying between the soil layer and water table (Kabera and

Fig. 7 Slope percentage map of the study area

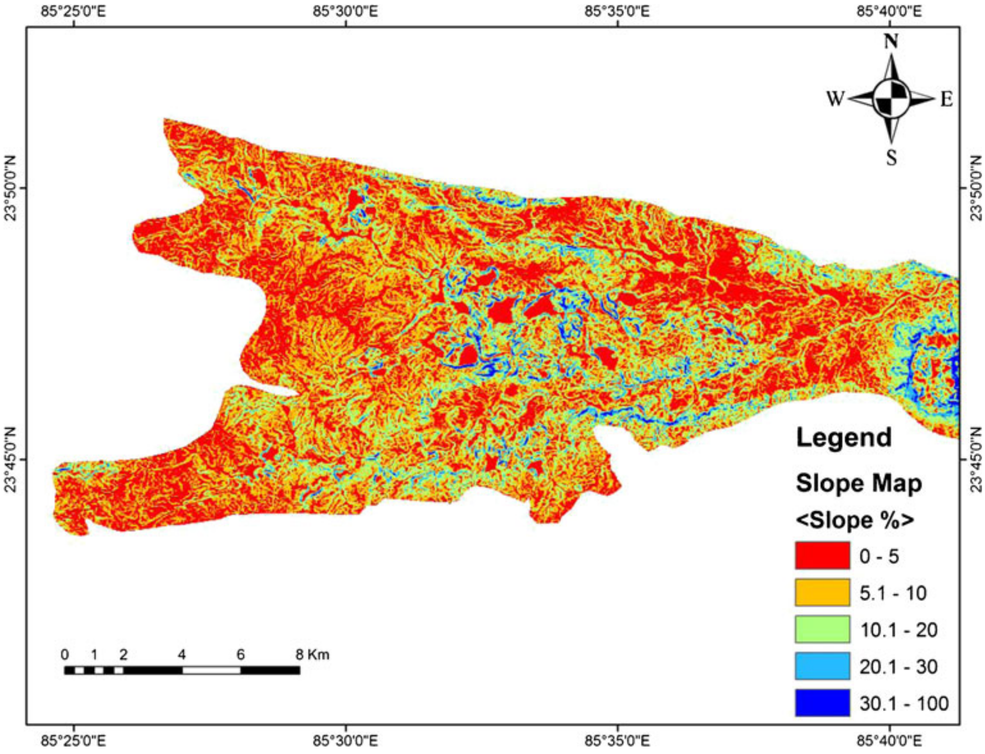
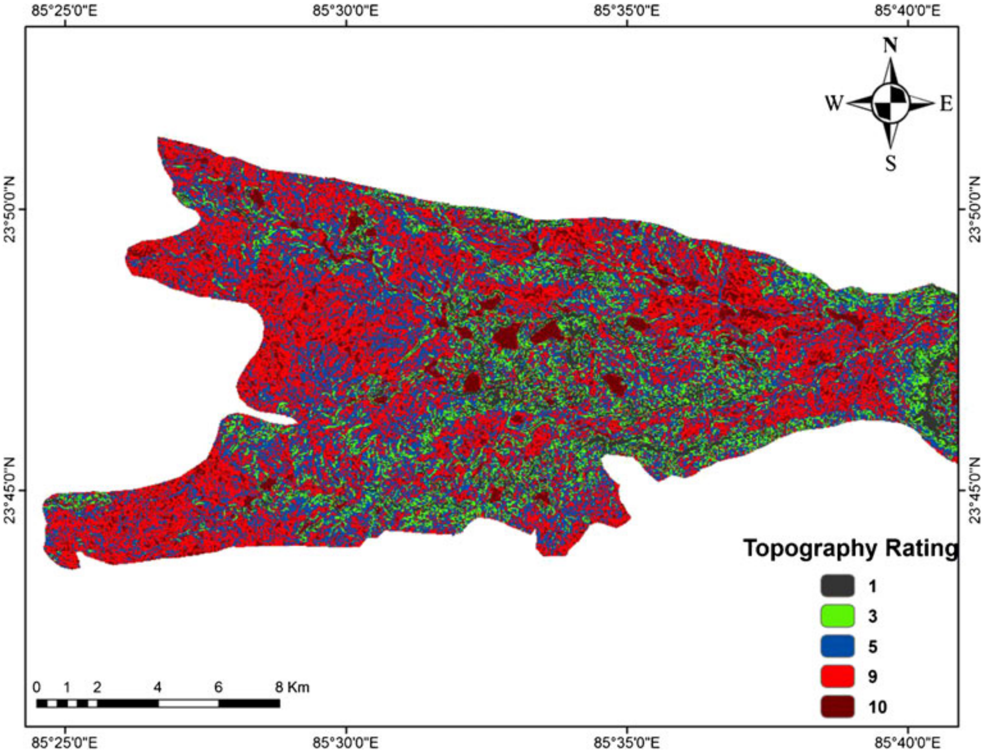
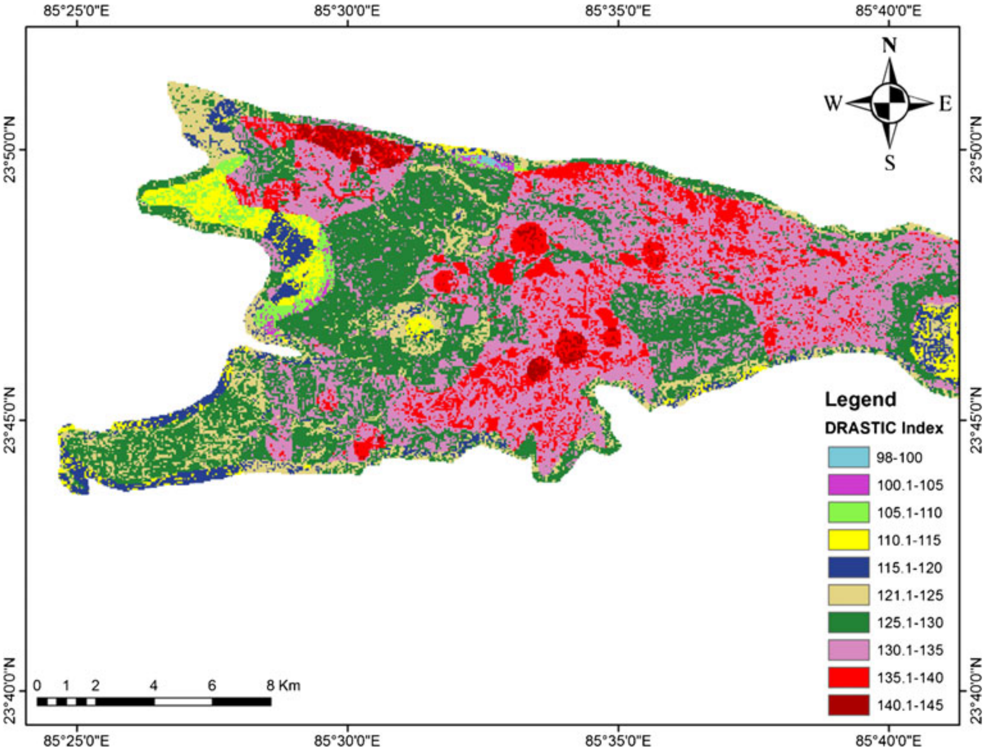


Fig. 8 Topography rating map of the study area



Zhaohui 2008). This factor affects the flow rate at the surface and consequently affects biodegradation and attenuation (Baalousha 2006). The movement of water within the vadose zone is studied in hydrogeology and is of importance to contaminant transport. The vadose zone map was prepared from the lithological cross sections obtained from the borehole data. The typical value of 6 has been assigned to the vadose zone of the area consisting of coarse to medium sandstone, grit and shale according to DRASTIC rating.

Fig. 9 DRASTIC index map of the study area



Hydraulic conductivity of the aquifer (*C*)

Hydraulic conductivity refers to the ability of aquifer materials to transmit water, which, in turn, controls the rate at which groundwater will flow under a given hydraulic gradient (Aller et al. 1987). Hydraulic conductivity values were calculated after calculating transmissibility from pumping test data and have been mapped. An aquifer with high conductivity is vulnerable to substantial contamination, as a plume of contamination can move easily through the aquifer Therefore, it is a function of the grain size, shape, sorting and packing of the aquifer materials and properties of the fluid passing through the aquifer. On this basis, hydraulic conductivity (k) was estimated on the ranges provided in the DRASTIC method and validated using values from the literature and pumping test data of the study area. The hydraulic conductivity range varied from 12.3 to 24.5 GPD/ft^2 in the study area. The hydraulic conductivity zones in the area were defined and assigned a rating according to DRASTIC rating.

DRASTIC vulnerability index map

Aquifer vulnerability analysis was carried out as described in the DRASTIC model section. Combining the hydrogeological setting parameters results in a range of numerical values termed the DRASTIC index. By combining the seven DRASTIC parameter index values, a range of values are developed that have been classified to present aquifer vulnerability with the help of GIS. The vulnerability index values vary between 98 and 145. The DRASTIC rating index map of the study area is portrayed in Fig. 9. The original DRASTIC method published by Aller et al. (1987) does not provide vulnerability classification ranges but allows the user to interpret the vulnerability index using their own field knowledge and hydrogeological experience. The commonly used vulnerability index classification system used in the literature defines four classes of vulnerability: low vulnerability (<100), moderate vulnerability (101–120), moderate to high vulnerability (121–140) and high vulnerability (140). Thus, the vulnerability zones of the West Bokaro coalfield were obtained according to the indication of indexes as seen in Fig. 10. Using this classification, an aquifer vulnerability potential map was generated which shows that 0.06 % of the area falls into the low-vulnerability zone and 10.8 % falls into the moderate vulnerability zone. About 87.7 % of the study area falls into moderate to high-vulnerability zone, and 1.4 % of the study area was classified as a highly vulnerable zone (Table 3). A perusal of the vulnerability map shows that some western parts and some

Table 3 Vulnerability zone distribution

Drastic range	Area (km^2)	Area (%)	Vulnerability rating
<100	0.12	0.06	Low
101–120	22.4	10.8	Moderate
121–140	181.6	87.7	Moderate to high
>140	2.9	1.4	High

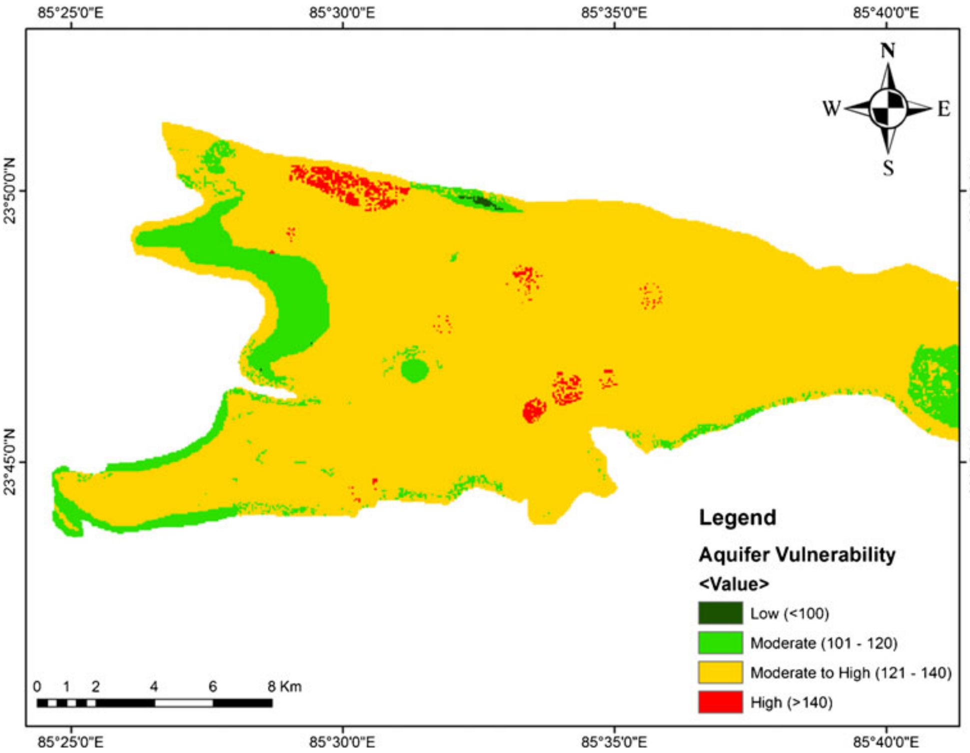


Fig. 10 Aquifer vulnerability map of the study area

Table 4 Statistical summary of the DRASTIC parameter map

	D	R	A	S	T	I	C
Minimum	5	3	2	2	1	6	1
Maximum	10	6	6	6	10	6	1
Mean	9	6	5	4	7	6	1

middle parts have a high-vulnerability zone and therefore are more susceptible to aquifer pollution.

Validation of DRASTIC result

Statistical analysis of the seven rated parameters of the DRASTIC model was used to work out the vulnerability of the aquifer in the West Bokaro coalfield region (Table 4). We found that the means of the parameters reveal that the primary contribution to the vulnerability index is made by depth-to-water table (mean = 9) and the secondary contribution is topography (means = 7). Net recharge (mean = 6) and vadose zone (mean = 6) are third significant parameters. The aquifer and soil media have mean values of 5 and 4, so contribute least to the contamination of the aquifer. The vulnerability index map validated with the observed SO_4^{2-} and Fe concentrations in the groundwater of the study area. The reason behind the selection of SO_4^{2-} was that the major sources of SO_4^{2-} in the groundwater of the area are due to geogenic (Tiwari et al. 2016a). However, the reason behind the selection of Fe was that the major sources of Fe in the groundwater of the area are due to the mining and related activities (Tiwari et al. 2016b). Previous studies by Neves and Matias (2008); Yellishetty et al. (2009); Tripathy (2010); Utom et al. (2013) and Mahato et al. (2014) indicate that coal mining and other mining-related operations release Fe into the water resources. Table 5 gives the reported concentration range of parameters in the water resources of Indian mining regions with sources from different studies. Groundwater samples were collected from 33 locations in the West Bokaro coalfield area, and concentrations of SO_4^{2-} and Fe were determined by using ion chromatograph (Dionex Dx-120) and inductively coupled plasma-mass spectroscopy (ICP-MS, PerkinElmer, Model: ELAN DRCe). Figures 11 and 12 clearly indicate that the trends of SO_4^{2-} and Fe concentrations and vulnerability index maps (Figs. 9 and 10) were matched closely in most of the occasions, except in a few places. Figures 11 and 12 clearly indicate that the SO_4^{2-} and Fe concentrations in the samples lie in level 3 (101–200 mg L^{-1}) and (401–600 µg L^{-1}) were mainly stretched out in the class of moderate to high-vulnerability zone. It was observed that some samples had SO_4^{2-} and Fe concentration levels greater than 200 mg L^{-1} and 600 µg L^{-1}, which is in level 4, and this location was stretched out in the high-vulnerability zone, except in a few places. This clearly indicates that the SO_4^{2-} and Fe validation can be accepted for vulnerability assessment.

Conclusions

The vulnerability map thus generated helps in identifying areas which are more likely to be susceptible to groundwater contamination. The aquifer vulnerability potential map shows that the bulk of the area is covered by the high moderate vulnerable zone followed by the medium-vulnerability zones. The Pundi, Parej, Kedla, near Ara and Sarubera coal mines are located in the highly vulnerable zone. Some of the western parts were classified as a high vulnerability index, which is attributed to shallow of

Table 5 Details about high-concentration range of parameters in the water resources of Indian mining regions

Type of water and location	TDS (mg L^{-1})	SO_4^{2-} (mg L^{-1})	TH (mg L^{-1})	Ni (µg L^{-1})	Fe (µg L^{-1})	Sources	References
Mine water, Central Coalfield Limited	200–670	25–185	260–570	–	250–1770	Mining	Tiwary (2001)
Groundwater, Damodar River basin	123–1552	2.5–713	41.8–949	–	–	Geogenic and mining	Singh et al. (2008)
Mine water, Raniganj coalfield	171–1626	3.9–586	48–863	6.5–110.2	71–973	Geogenic	Singh et al. (2010)
Mine water, Jharia coalfield	512–1341	18–768	246–1206	1.7–24.4	219–838	Geogenic and mining	Singh et al. (2011)
Groundwater, West Bokaro coalfield	101–1073	25–359	52–586	0.5–36[a] 1.0–44[b]	308–895[a] 491–1321[b]	Geogenic and mining	Tiwari et al. (2016a, b)
Mine water, West Bokaro coalfield	349–1029	98–545	203–651	–	–	Geogenic	Tiwari et al. (2016c)

TH total hardness, *TDS* total dissolved solids

[a] In the post-monsoon season

[b] In the pre-monsoon season

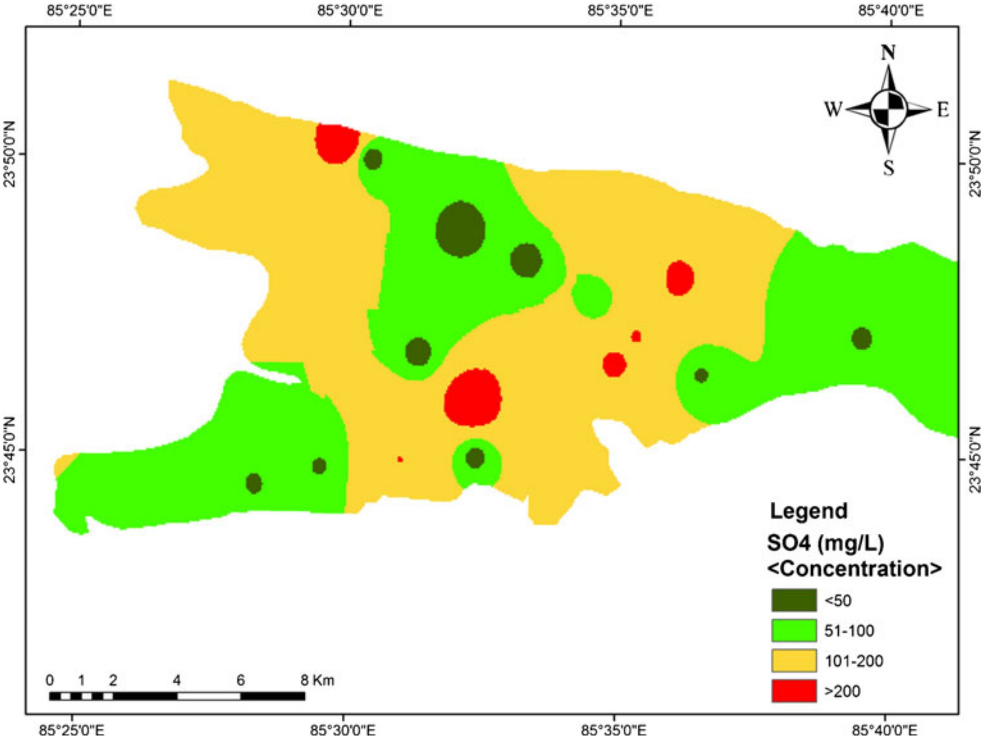


Fig. 11 SO_4^{2-} concentration map for validation of vulnerability index map

water level, topography, high net recharge and permeable vadose zone. The few patches in the middle part of the study area are characterized by a high vulnerability index, which, in turn, is attributed to the shallow water level and topography of the area. The fact which clearly emerges from the study is that the depth-to-water level, topography, high net recharge and permeable vadose zone of the area served as the most influential parameters in mapping the vulnerability. However, the impact of the remaining parameters cannot be ruled out. This study also highlights

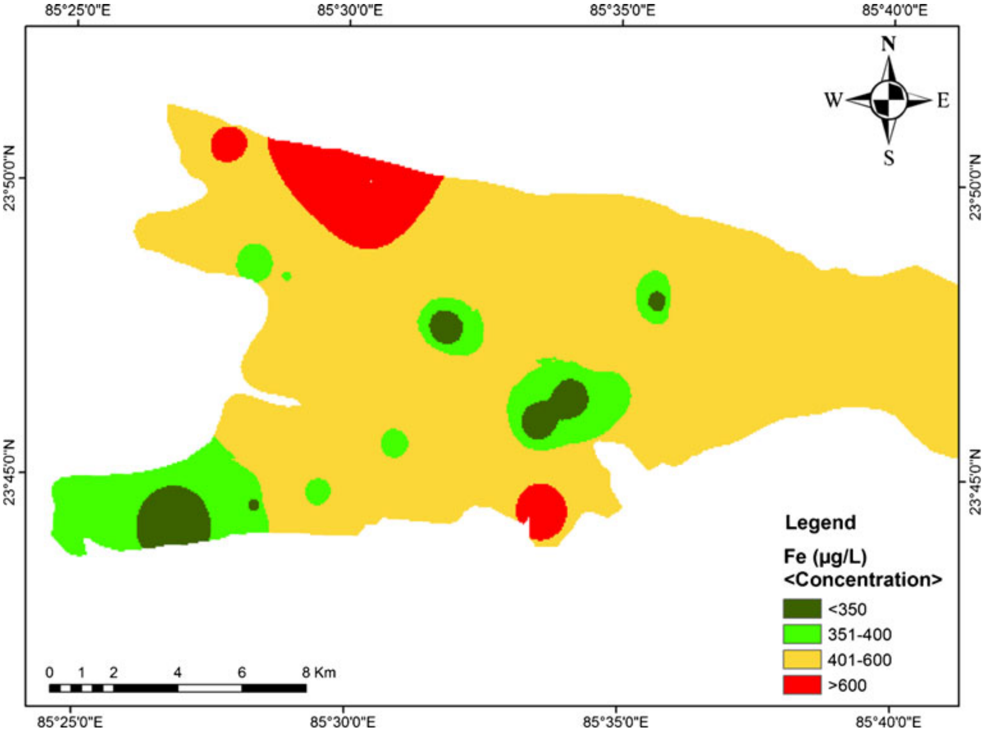


Fig. 12 Fe concentration map for validation of vulnerability index map

that mining and related activities are responsible for the high aquifer vulnerability of the area. This research suggests that the aquifer vulnerability status evaluation program should be performed at least once in every six months to twelve months interval for proper management of water resources in the mining regions.

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References

Al Zebet T (2002) Evaluation of aquifer vulnerability to contamination potential using the DRASTIC method. Environ Geol 43: 203–208

Albinet M, Margat J (1970) Cartographie dela vulnerability pollution des nappes d'eau souterraine [Mapping of groundwater vulnerability to contamination]. Bull BRGM 2(4):13–22

Aller L, Bennet T, Leher JH, Petty RJ, Hackett G (1987) DRASTIC: a standardized system for evaluating ground water pollution potential using hydro-geological settings. EPA 600/2–87-035:622

Baalousha H (2006) Vulnerability assessment for the Gaza Strip, Palestine using DRASTIC. Environ Geol 50:405–414

Babiker IS, Mohamed MA, Hiyama T, Kato K (2005) A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. Sci Total Environ 345:127–140

Bhuiyan MA, Islam MA, Dampare SB, Parvez L, Suzuki S (2010) Evaluation of hazardous metal pollution in irrigation and drinking water systems in the vicinity of a coal mine area of northwestern Bangladesh. J Hazard Mater 179(1):1065–1077

Chitsazan M, Akhtari Y (2009) A GIS-based DRASTIC model for assessing aquifer vulnerability in Kherran Plain, Khuzestan, Iran. Water Resour Manage 23(6):1137–1155

Civita M, M De Maio (1997) SINTACS Un sistema parametrico per la valutazione e la cartografia della vulnerabilità degli acquiferi all'inquinamento. Metodologia e automazione. Pitagora Editrice, Bologna, 191

Ckakraborty S, Paul PK, Sikdar PK (2007) Assessing aquifer vulnerability to arsenic pollution using DRASTIC and GIS of north Bengal Plain: a case study of English Bazar Block, Malda District, west Bengal, India. J Spatial Hydro 7(1):101–121

COST 65 (1995) Hydrogeological aspects of groundwater protection in karstic areas, Final report (COST action 65). European Commission, Directorate-General XII Science, Research and Development, Report EUR 16547 EN, Brussels, p. 446

Doerfliger N, Zwahlen F (1998) Practical guide, groundwater vulnerability mapping in karstic regions (EPIK). Swiss Agency for the Environment, Forests and Landscape (SAEFL), Bern, 56 pp

Edet A (2014) An aquifer vulnerability assessment of the Benin Formation aquifer, Calabar, southeastern Nigeria, using DRASTIC and GIS approach. Environ Earth Sci 71(4):1747–1765

Farjad B, Mohd B, Shafri HZ, Mohamed TA, Pirasteh S, Wijesekara N (2012) Groundwater intrinsic vulnerability and risk mapping. Proc ICE-Water Manage 165(8):441–450

Foster SD (1987) Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: Waegeningh HG, van WV (eds) The Hague. Vulnerability of soil and groundwater to pollutants 38: 69–86

Foster SSD (1988) Groundwater recharge and pollution vulnerability of British aquifers: a critical overview. Geological Society Special Publication 130 London

Freeze R, Cherry A (1979) Groundwater. Prentice-Hall, Englewood I Cliffs, N.]. USA 12(1987):145–165

Fritch TG, McKnight CL, Yelderman JC Jr, Arnold JG (2000) An aquifer vulnerability assessment of the Paluxy aquifer, central Texas, USA, using GIS and a modified DRASTIC approach. Environ Manag 25(3):337–345

Ghosh A, Tiwari AK, Das S (2015) A GIS based DRASTIC model for assessing groundwater vulnerability of Katri Watershed, Dhanbad, India. Model Earth Syst Environ 1(3):1–14

Goldscheider N, Klute M, Sturm S, Hotzl H (2000) The PI method: a GIS-based approach to mapping groundwater vulnerability with special consideration of karst aquifers. Z Angew Geol 463:157–166

Ground Water Resource Estimation Methodology (1997) Report of the Ground Water Resource Estimation Committee. Ministry of Water Resources Government of India, New Delhi

Ground Water Resource Estimation Methodology (2009) Report of the Ground Water Resource Estimation Committee. Ministry of Water Resources. Government of India, New Delhi

Jha MK, Sebastian J (2005) Vulnerability study of pollution upon shallow groundwater using drastic/GIS. In A paper presented in the 8th Annual International Conference and Exhibition in India, Map India. Geomatics, New Delhi, India

Kabera T, Zhaohui L (2008) A GIS based DRASTIC model for assessing groundwater in shallow aquifer in Yuncheng Basin, Shanxi, China. Res J Appl Sci 3(3):195–205

Krishna R, Iqbal J, Gorai AK, Pathak G, Tuluri F, Tchounwou PB (2014) Groundwater vulnerability to pollution mapping of Ranchi district using GIS. Appl Water Sci:1–14

Magiera P (2000) Methoden zur Absch tzung der Verschmutzungsempfindlichkeit des Grundwassers [Methods of assessing groundwater vulnerability]. Grundwasser 3:103–114

Mahato MK, Singh PK, Tiwari AK (2014) Evaluation of metals in mine water and assessment of heavy metal pollution index of East Bokaro Coalfield area, Jharkhand, India. Int J Earth Sci Eng 7(04):1611–1618

Margat J (1968) Vulnerabilite des mappes d'eau souterraine a la pollution. BRGM Publication, Orleans

Mondal GC, Singh AK, Singh TB, Singh S, Singh KK, Tewary BK (2009) Assessment of air quality in and around West-Bokaro coalfield, Hazaribag. Indian J Environ Prot 29(7):577–591

Nasri N, Chebil M, Guellouz L, Bouhlila R, Maslouhi A, Ibnoussina M (2014) Modelling nonpoint source pollution by nitrate of soil in the Mateur plain, northeast of Tunisia. Arab J Geosci 8(2):1057–1075

National Research Council (1993) Groundwater vulnerability assessment, contamination potential under conditions of uncertainty. National Academy Press, Washington, DC, 210 pp. Accessed December 2000 at: /http://books.nap.edu/books/0309047994/htmlS

Neves O, Matias MJ (2008) Assessment of groundwater quality and contamination problems ascribed to an abandoned uranium mine (Cunha Baixa region, Central Portugal). Environ Geol 53(8): 1799–1810

Olıas M, Nieto JM, Sarmiento AM, Cerón JC, Cánovas CR (2004) Seasonal water quality variations in a river affected by acid mine drainage: the Odiel River (South West Spain). Sci Total Environ 333(1):267–281

Panagopoulos GP, Bathrellos GD, Skilodimou HD, Martsouka FA (2012) Mapping urban water demands using multi-criteria analysis and GIS. Water Resour Manag 26(5):1347–1363

Papadopoulou-Vrynioti K, Alexakis D, Bathrellos GD, Skilodimou HD, Vryniotis D, Vassiliades E (2014) Environmental research and evaluation of agricultural soil of the Arta plain, western Hellas. J Geochem Explor 136:84–92

Papadopoulou-Vrynioti K, Alexakis D, Bathrellos GD, Skilodimou HD, Vryniotis D, Vassiliades E, Gamvroula D (2013) Distribution of trace elements in stream sediments of Arta plain (western Hellas): the influence of geomorphological parameters. J Geochem Explor 134:17–26

Pathak DR, Hiratsuka A, Awata I, Chen L (2009) Groundwater vulnerability assessment in shallow aquifer of Kathmandu Valley using GIS-based DRASTIC model. Environ Geol 57(7):1569–1578

Pradhan SP, Vishal V, Singh TN, Singh VK (2014) Optimization of dump slope geometry vis-a`-visflyash utilization using numerical simulation. Am J Min Metall 2(1):1–7

Prasad RK, Singh VS, Krishnamacharyulu SKG, Banerjee P (2011) Application of drastic model and GIS: for assessing vulnerability in hard rock granitic aquifer. Environ Monit Assess 176(1–4):143–155

Rahman A (2008) A GIS based model for assessing groundwater vulnerability in shallow aquifer in Algarh, India. Appl Geogr 28(1):32–53

Saha D, Alam F (2014) Groundwater vulnerability assessment using DRASTIC and Pesticide DRASTIC models in intense agriculture area of the Gangetic plains, India. Environ Monit Assess 186(12): 8741–8763

Samey AA, Gang C (2008) A GIS based DRASTIC model for the assessment of groundwater vulnerability to pollution in West Mitidja: Blida City, Algeria. J Appl Sci 3(7):500–507

Sener E, Sener S, Davraz A (2009) Assessment of aquifer vulnerability based on GIS and DRASTIC methods: a case study of the Senirkent-Uluborlu Basin (Isparta, Turkey). Hydro J 17(8):2023–2035

Shirazi SM, Imran HM, Akib S, Yusop Z, Harun ZB (2013) Groundwater vulnerability assessment in the Melaka State of Malaysia using DRASTIC and GIS techniques. Environ Earth Sci 70(5):2293–2304

Singh AK, Mahato M, Neogi B, Singh KK (2010) Quality assessment of mine water in the Raniganj coalfield area, India. Mine Water Environ 29:248–262

Singh AK, Mahato MK, Neogi B, Mondal GC, Singh TB (2011) Hydrogeochemistry, elemental flux, and quality assessment of mine water in the Pootkee-Balihari mining area, Jharia coalfield, India. Mine Water Environ 30(3):197–207

Singh AK, Mondal GC, Kumar S, Singh TB, Tewary BK, Sinha A (2008) Major ion chemistry, weathering processes and water quality assessment in upper catchment of Damodar River basin, India. Environ Geol 54:745–758

SNIFFER (Scotland and Northern Ireland Forum for Environmental Research) (2004) Development of a groundwater vulnerability screening methodology for the water framework directive. Project report code WFD 28, September 2004, Edinburgh

Tiwari AK, De Maio M, Singh PK, Singh AK (2016a) Hydrogeochemical characterization and groundwater quality assessment in a coal mining area, India. Arabian J Geosci 9(3):1–17. doi: 10.1007/s12517-015-2209-5

Tiwari AK, Singh PK, Singh AK, De Maio M (2016b) Estimation of heavy metal contamination in groundwater and development of a heavy metal pollution index by using GIS technique. Bull Environ Contam Toxicol 96:508–515. doi:10.1007/s00128-016-1750-6

Tiwari AK, Singh PK, Mahato MK (2016c) Environmental geochemistry and a quality assessment of mine water of the West Bokaro Coalfield, India. Mine Water Environ. doi:10.1007/s10230-015-0382-0

Tiwary RK (2001) Environmental impact of coal mining on water regime and its management. Water Air Soil Pollut 132:185–199

Tripathy DP (2010) Determination of trace elements concentration and trace elements index in mine water in some fire and non-fire affected areas of Jharia coalfield, India. Pollut Res 29:385–390

Trivedi R, Vishal V, Pradhan SP, Singh TN, Jhanwar JC (2012) Slope stability analysis in Limestone mines. Int J Earth Sci Eng 5(4):759–766

Umar R, Ahmed I, Alam F (2009) Mapping groundwater vulnerable zones using modified DRASTIC approach of an alluvial aquifer in parts of Central Ganga Plain, Western Uttar Pradesh. J Geo Soc India 73(2):193–201

Utom AU, Odoh BI, Egboka BC (2013) Assessment of hydrogeochemical characteristics of groundwater quality in the vicinity of Okpara coal and Obwetti fireclay mines, near Enugu town, Nigeria. Appl Water Sci 3(1):271–283

Vierhuff HW, Aust WH (1981) Die Grundwasservorkommen in der Bundesrepublik Deutschland. Geologisches Jahrbuch, Band C30: 3–110

Vishal V, Pradhan SP, Singh TN (2010) Instability analysis of mine slope by finite element method approach. Int J Earth Sci Eng 3(6):11–23

Vrba J, Zaporozec A (1994) Guidebook on mapping groundwater vulnerability. Int Contrib Hydrogeol Nr. 16, Hannover

Yellishetty M, Ranjith PG, Kumar DL (2009) Metal concentrations and metal mobility in unsaturated mine wastes in mining areas of Goa, India. Reso Conser Recyc 53(7):379–385