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Estimation of Heavy Metal Contamination in Groundwater and Development of a Heavy Metal Pollution Index by Using GIS Technique

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Abstract Heavy metal (Al, As, Ba, Cr, Cu, Fe, Mn, Ni, Se and Zn) concentration in sixty-six groundwater samples of the West Bokaro coalfield were analyzed using inductively coupled plasma-mass spectroscopy for determination of seasonal fluctuation, source apportionment and heavy metal pollution index (HPI). Metal concentrations were found higher in the pre-monsoon season as compared to the post-monsoon season. Geographic information system (GIS) tool was attributed to study the metals risk in groundwater of the West Bokaro coalfield. The results show that 94 % of water samples were found as low class and 6 % of water samples were in medium class in the post-monsoon season. However, 79 % of water samples were found in low class, 18 % in medium class and 3 % in high class in the pre-monsoon season. The HPI values were below the critical pollution index value of 100. The concentrations of Al, Fe, Mn, and Ni are exceeding the desirable limits in many groundwater samples in both seasons.

Keywords Groundwater quality · GIS · HPI · Heavy metals · PCA · Seasonal variation · Source evaluation · West Bokaro coalfield

The present study is a continuation of our work on evaluation of heavy metal contamination of water resources in the West Bokaro coalfield area by using a HPI and GIS technique (Tiwari et al. 2015). In this study, we evaluate the distribution of some selected heavy metals (Al, As, Ba, Cr, Cu, Fe, Mn, Ni, Se and Zn) in the groundwater of the West Bokaro coalfield using a heavy metal pollution index (HPI) and geographic information system (GIS). The information of the heavy metal contamination is very useful for utilization of groundwater resources that may also help in future water resource planning for the mining area. The concentrations of most of the metals are usually very low in unaffected environments and mostly derived from the mineralogy and weathering (Karbassi et al. 2007). Main anthropogenic sources of heavy metal contamination are mining, disposal of untreated and partially treated effluents containing toxic metals as well as metal chelates from different industries and indiscriminate use of heavy metal-containing fertilizer and pesticides in agricultural fields (Ammann et al. 2002; Nouri et al. 2008). Mining and related activities are causing water pollution and threatens the quality and quantity of surface and groundwater resources (Tiwary 2001; Verma and Singh 2013; Singh et al. 2013c). There are no proper water management plans in most of the mines in India, major part of mine water is discharged into the open channels without any treatment or beneficial use. Mine water can vary greatly in the concentration of contaminants present, and in some cases it may even meet the drinking water specification.

Groundwater is an important water source for the agricultural purposes, industrial sectors and majorly used as potable water in India (Singh et al. 2014; Chandra et al. 2015). However, availability of clean and potable drinking water emerged as one of the most serious developmental issue in many parts of India including Jharkhand in recent

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years (Tiwari and Singh 2014). Water quality indices are one of the most effective tools to communicate information on the quality of any water body (Singh et al. 2013a). The heavy metal pollution index (HPI) is a technique of rating that provides the overall quality of water with respect to the heavy metals. In recent past many researchers have used various water quality indices for assessing quality of water (Kumar et al. 2012; Prasanna et al. 2012; Yankey et al. 2013; Mahato et al. 2014; Varghese and Jaya 2014; Selvam et al. 2015; Singh et al. 2015; Yadav et al. 2015; Jahanshahi and Zare 2015; Gautam et al. 2015; Singh and Kamal 2015; Singaraja et al. 2015; Krishan et al. 2016 and several others).

Materials and Methods

The West Bokaro coalfield lies between 23°41′ to 23°52′ N latitude and 85°24′ to 85°41′ E longitude (Fig. 1). The geology of the study area consists of Barakar Formation, Barren Measures, Mahadeva, Metamorphics, Panchet, Raniganj and Talchir Formation (Fig. 1). The topography of the region lies between 229 and 660 m above the sea level. The hypsometric curve of the region shows that about 61.8 % of the area has elevation between 229 and 350 m and 36.6 % between 350 and 400 m and small area i.e. 1.6 % above 400 m. Previous studies have also been conducted on role of different factor in other kind of slope in mines (Vishal et al. 2010; Pradhan et al. 2014). The average annual rainfall of the district is 1418 mm and more than 85 % of annual rainfall occurs during the four monsoon months (June to September). Details about climate, drainage and geology of the West Bokaro coalfield are described elsewhere (Tiwari et al. 2015).

Total sixty-six groundwater samples were collected from thirty-three locations during the post-monsoon (November, 2012) and the pre-monsoon (May, 2013) seasons in prewashed 100 mL narrow mouth polyethylene bottles for analysis of the heavy metals (Fig. 1). Concentration of heavy metals (Al, As, Ba, Cr, Cu, Fe, Mn, Ni, Se and Zn) in acidified groundwater samples were determined by using inductively coupled plasma-mass spectroscopy (ICP–MS, Perkin Elmer, Model: ELAN DRCe). Details about preparation of samples for heavy metals analysis and the accuracy of the analysis and calibration verification standard procedures are described elsewhere (Tiwari et al. 2015).

Principal component analysis (PCA) technique extracts eigenvalues and eigenvectors from the covariance matrix

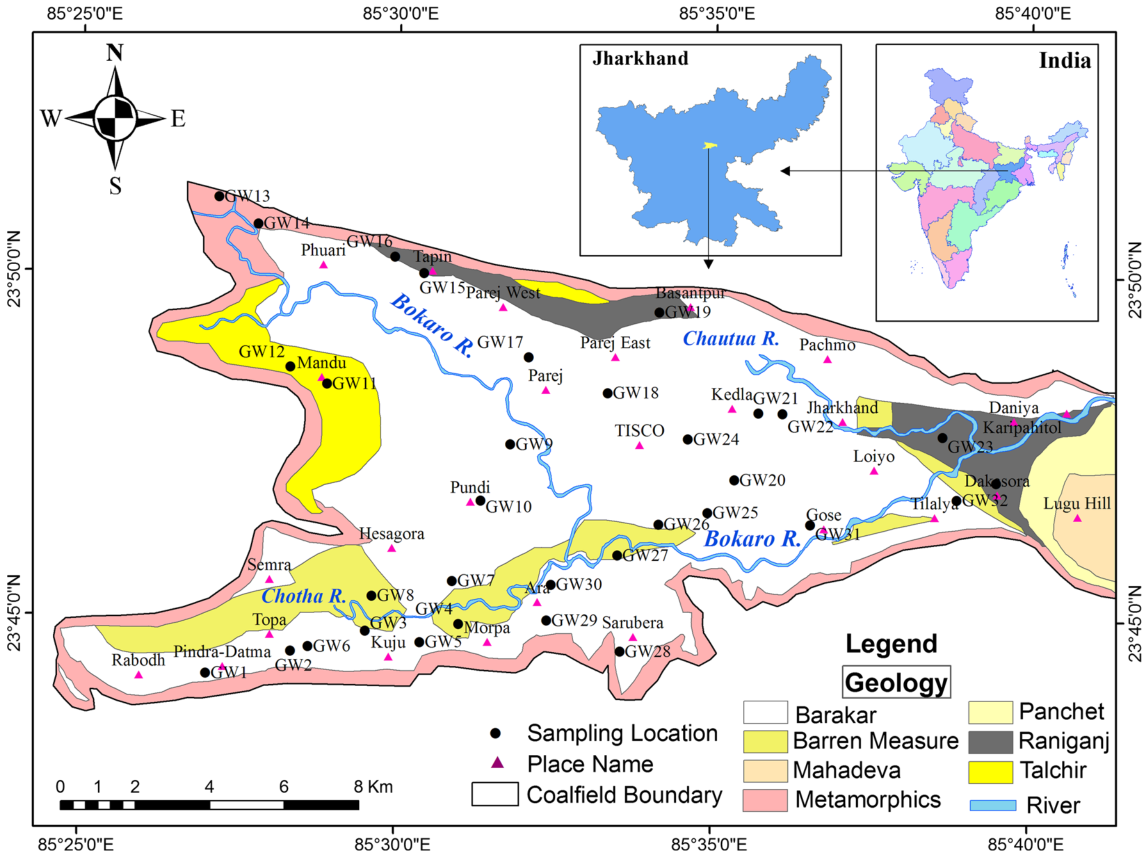

Fig. 1 Sampling locations and geological map of the West Bokaro coalfield

Table 1 Seasonal variation in metal concentration in the groundwater of the West Bokaro coalfield and comparison with drinking water guidelines values of WHO (2006), BIS (2003) and USEPA (2009) (unit: μg L^{-1})

Locations	Al	As	Ba	Cr	Cu	Fe	Mn	Ni	Se	Zn
Post-monsoon (n = 33)										
Minimum	13.7	0.1	29.4	0.04	0.3	308	1.3	0.5	0.24	5.4
Maximum	174.4	0.7	98.7	6.4	5.7	895	139	36	2	45.5
Average	35.4	0.32	54.5	0.8	1.2	476	28.6	9.4	0.7	14.3
Pre-monsoon (n = 33)										
Minimum	14.3	0.2	38	0.4	0.4	491	2.6	1.0	0.3	9.8
Maximum	679	1.3	236	9.5	29.5	1321	191	44	2.8	117.4
Average	90	0.5	79	2.8	4.1	880	53	21	0.9	33
WHO (2006)	100–200	10	300	50	2000	300	100	20	10	4000
BIS (2003)	–	50	1000	50	50	300	100	–	10	5000
USEPA (2009)	50–200	10	2000	100	1300	300	50	–	50	5000

of original variables. Principal component analysis is a powerful pattern recognition tool that attempts to explain the variance of a large dataset of inter-correlated variables with a smaller set of independent variables (Simeonov et al. 2003). Factor analysis further reduces the contribution of less significant variables obtained from PCA. The new group of variables known as varifactors (VF) is extracted through rotating the axis along with the variables obtained from PCA (Vega et al. 1998).

The method described in our previous study (Tiwari et al. 2015) has been followed for calculation and classification of HPI value. Briefly, three classes have been demarcated as low (<15 HPI), medium (<15–30 HPI) and high (>30 HPI) values as suggested by Edet and Offiong (2002). The concentration limits [i.e. highest permissive value for drinking water (S_i) and maximum desirable value (I_i) for each parameter] were taken from the Indian drinking water specifications (BIS 2003, IS:10500). The HPI model (Mohan et al. 1996) is given by Eq. (1)

$$\mathrm{HPI} = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

where, Q_i is the sub-index of the ith parameter. W_i is the unit weightage of ith parameter, and n is the number of parameters considered. The sub index (Q_i) of the parameter is calculated by Eq. (2)

$$Q_i = \sum_{i=1}^{n} \frac{\{M_i(-)I_i\}}{(S_i - I_i)} \tag{2}$$

where M_i is the monitored value of heavy metal of ith parameter, I_i is the ideal value of the ith parameter and S_i is the standard value of the ith parameter. The sign (−) indicates numerical difference of the two values, ignoring the algebraic sign.

Geographic information system (GIS) is most effective tool to provide better information of the consumers, policy makers and this helps for taking quick decision. For the spatial distribution map at 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 spatial distributions of HPI value were done with the help of spatial analyst module in ArcGIS software. Inverse distance weighted (IDW) interpolation technique was used for spatial modelling.

Results and Discussion

The statistical results of the heavy metals analysis for the post- and pre-monsoon seasons are presented in Table 1. The average concentration of Al, As, Ba, Cr, Cu, Fe, Mn, Ni, Se and Zn of the entire sample in the post-monsoon season was found as 35.4, 0.32, 54.5, 0.8, 1.2, 476, 28.6, 9.4, 0.7 and 9.3 μg L^{-1} respectively. The mean concentration of Al, As, Ba, Cr, Cu, Fe, Mn, Ni, Se and Zn in the pre-monsoon season was found 90, 0.5, 79, 2.8, 4.1, 880, 53, 12.3, 0.9 and 27.2 μg L^{-1} respectively. In the post-monsoon season, the concentrations of the metals were found lower as compared to the pre-monsoon season.

After the comparison of result with the drinking water guidelines of WHO (2006), USEPA (2009) and Indian standards (BIS 2003), it was observed that Al, Fe, Mn, and Ni in the post- and pre-monsoon seasons were found in higher concentration than the level of drinking water in different sampling location (Table 1). This is interesting to note that variations of seasonal input to groundwater are mainly due to the hydrological regime and mining activities. The concentrations of Fe ranged from 308 to 895 μg L^{-1} (average 476 μg L^{-1}) in the post-monsoon season and 491–1321 μg L^{-1} (average 880 μg L^{-1}) in the

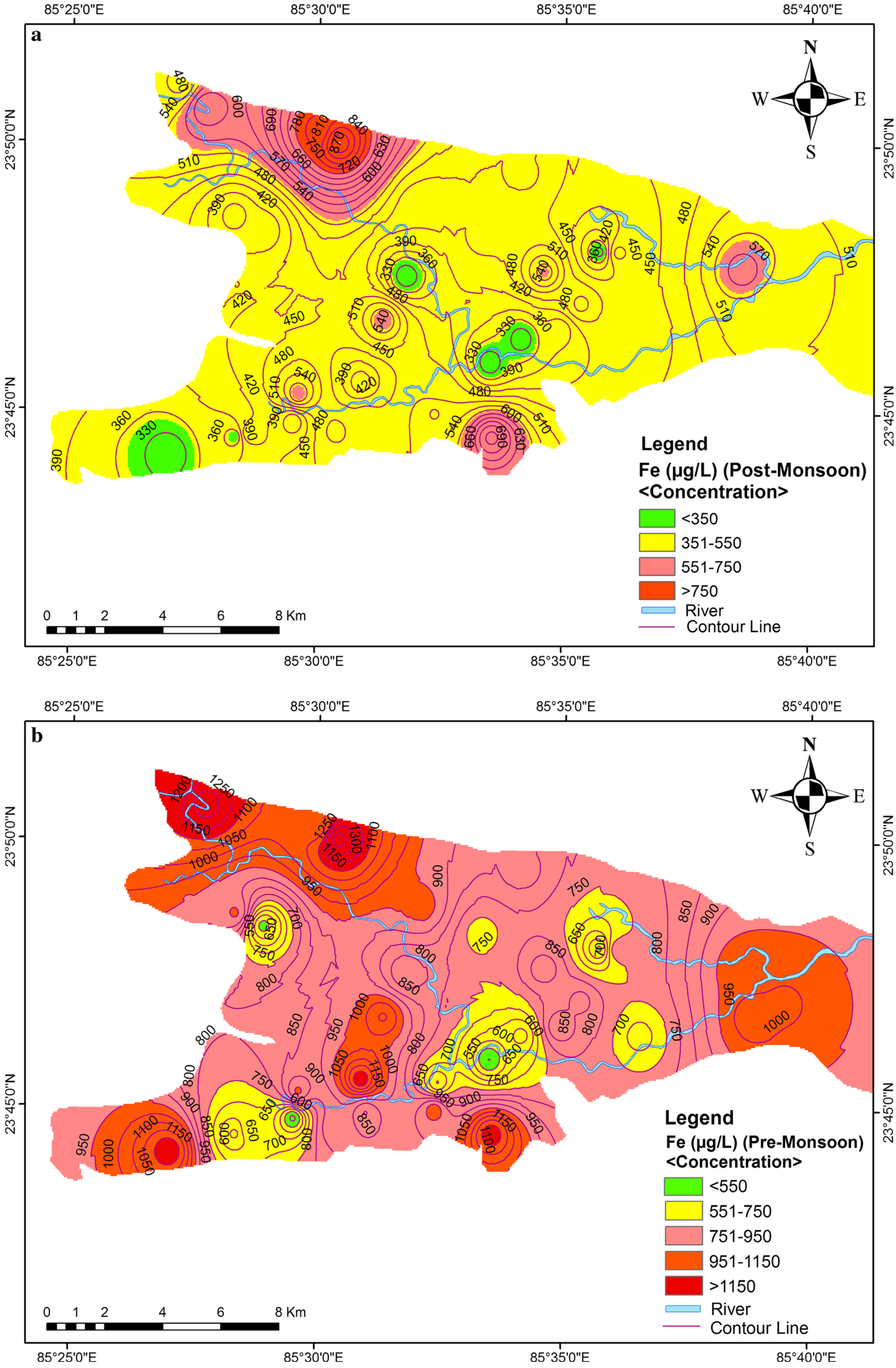

Fig. 2 Concentration contour showing spatial distribution for Fe in groundwater throughout the study area in the **a** post-monsoon season, **b** pre-monsoon season

pre-monsoon season, exceeding the desirable limit of 300 µg L^{-1} in all the groundwater samples in both seasons (Fig. 2a, b). Fe and Mn are common metallic elements found in the earth's crust (Kumar et al. 2010). Excess Fe in water is mostly accumulated through the weathering of rocks and industrial effluents discharge. The observed high value of Fe in the groundwater may be attributed to mine effluent and leachate water from overburden dumps of coal mines of the area. Previous studies by Tripathy (2010) and Mahato et al. (2014) indicate that coal mining and other mining related operations releases Fe in the environment. Excess iron causes endemic water quality problem in India (Singh et al. 2013b). The concentration of Mn ranged from 1.3 to 139 µg L^{-1} in the post-monsoon and 2.6 to 191 µg L^{-1} in the pre-monsoon, exceeding the desirable limit of 100 µg L^{-1} in 9 % and 24 % groundwater samples in the post-monsoon and pre-monsoon season respectively. High concentrations of Mn in the groundwater are due to the geological formation of the area (Senapaty and Behera 2012). The concentration of Ni ranged from 0.5 to 36 µg L^{-1} (average 9.4 µg L^{-1}) in the post-monsoon season and 1.0 to 44 µg L^{-1} (average 21 µg L^{-1}) in the pre-monsoon season, exceeding the desirable limit of 20 µg L^{-1} in 18 % and 52 % groundwater samples in the post-monsoon and pre-monsoon respectively. The Al, As, Cr, Cu, Ba, Se, and Zn concentration was higher in the pre-monsoon as compared to post-monsoon season irrespective of the locations.

Generally, the concentrations of the metals are higher in the pre-monsoon, while the lowest concentration was found in the monsoon and post-monsoon seasons which represent the heavy rainfall (Giri et al. 2012; Tiwari et al. 2015). The overall decrease in the relative concentration of metals from summer to monsoon is due to heavy local precipitation and seepage which not only dilutes the metals but also aids in their migration (Ramesh et al. 1995). It has been observed that water chemistry in mineralised areas with strong wet to dry rainfall patterns demonstrates a marked seasonality, with all solute concentrations decreasing during the rainy season owing to dilution through rainfall recharge. The fluctuations are due to the seasonality in groundwater flow, with high recharge and discharge during the rains and little to no further groundwater discharge by the middle dry season (Heyden and New 2004). This type of hydrologic response is expected to be the primary reason for the higher concentration of metals observed in the pre-monsoon season as compared to the post-monsoon season (Tiwari et al. 2015). The recharge of the groundwater in the monsoon, leads to the dilution of the heavy metals thus reducing its concentration. Similar observation have been made in the studies where monsoon is predominant pattern of rainfall (Dhakate and Singh 2008; Giri et al. 2012).

Principal component analysis (PCA) was adopted to assist the interpretation of elemental data. The PCA of groundwater showed that the variables were correlated to two principal components in which 62.7 % of the total variance was justified. Two factor with eigenvalues >1 have been extracted from the principal factor matrix after varimax rotation. The first factor (PC-I) seemed to be associated to the earth's crust and the geological formation of the area. The first component with 46.7 % of variance comprises Cu, Al, As, Ba, Mn, Cr, and Zn with high loadings (Table 2). The second component (PC-II) contributed Ni, Fe and Se and account for 16 % of the total variance. This factor can be attributed to the mining activities of the area. Mine effluent and leachate water from overburden dumps material of coal are the sources of these metals (Tiwari 2001; Bhuiyan et al. 2010).

In order to calculate the HPI of the groundwater, the mean concentration value of the selected metals (Al, As, Ba, Cr, Cu, Fe, Mn, Ni, Se and Zn) have been taken into account. The values of HPI was to be found in the range of 3–17 (mean 7) in the post-monsoon and 4–32 (mean 12) in the pre-monsoon season. The higher values of HPI have been found at sites 7 and 9 in the post-monsoon season and at sites 1, 2, 7, 9, 14, 17, 26, 28 in the pre-monsoon season. The higher values of HPI may be attributed to weathering of rocks and mining activities. Lower HPI values in the post-monsoon season indicate pollutants dilution affect of rain water. The HPI values of the samples within study area were found below the critical pollution index (100) in both seasons. However, considering the classes of HPI, all the locations for both seasons fall under the low class (HPI < 15), medium class (HPI 15–30) and high class (HPI > 30) (Fig. 3a, b). In the post-monsoon season the

Table 2 Principal component loadings (varimax normalized) for the metals in groundwater of the West Bokaro coalfield

Elements	PC-I	PC-II
Al	0.870	0.164
As	0.864	−0.031
Ba	0.733	0.234
Cr	0.650	0.621
Cu	0.895	−0.036
Fe	0.121	0.688
Mn	0.629	0.184
Ni	0.367	0.714
Se	0.122	0.553
Zn	0.582	0.558
Eigenvalues	4.6	1.6
%Total variance	46.7	16
Cumulative variance	46.7	62.7

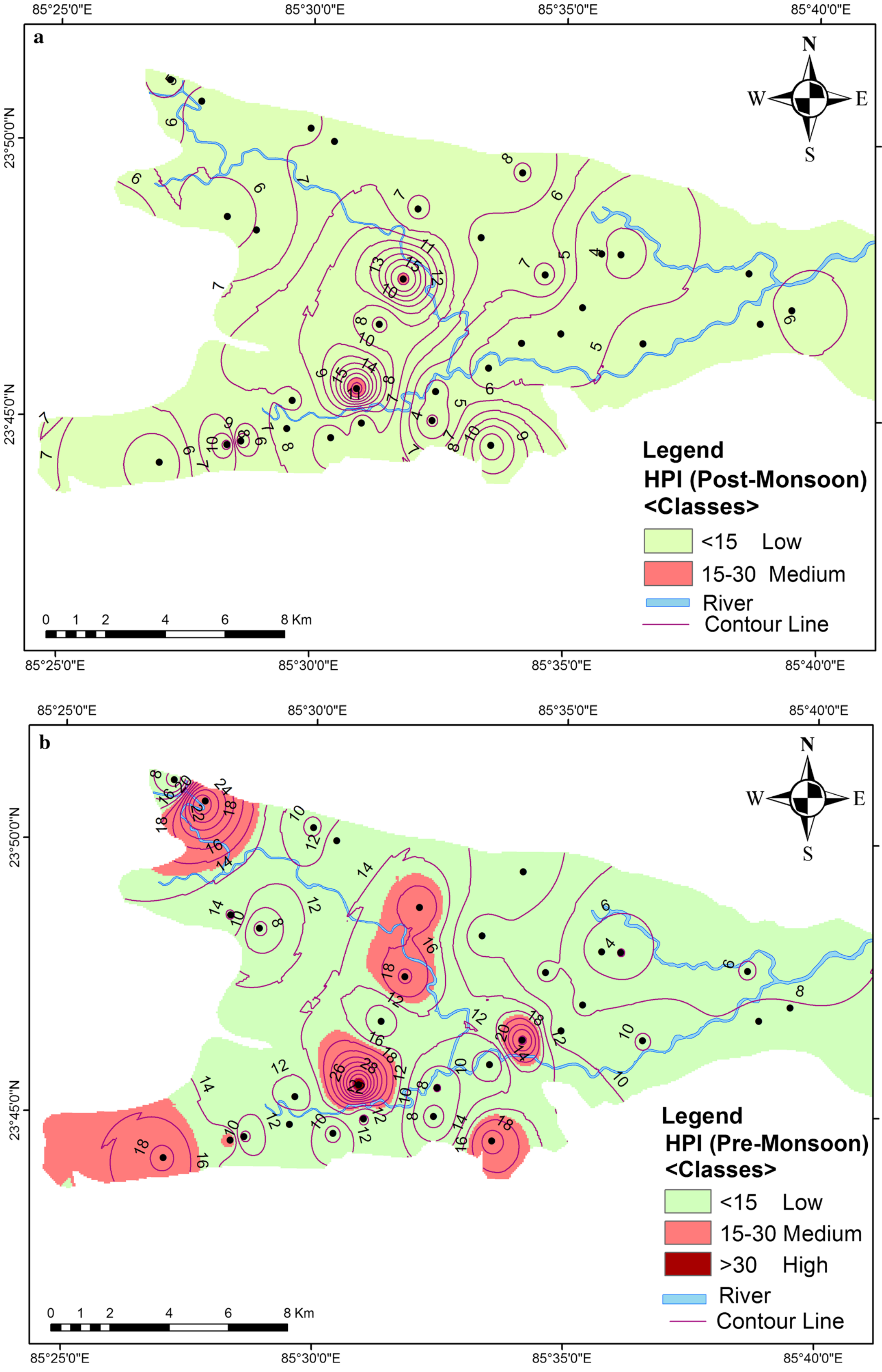

Fig. 3 Heavy metal pollution index class map of the West Bokaro coalfield area in the **a** post-monsoon season, **b** pre-monsoon season (after Edet and Offiong 2002)

percentage (%) of HPI classes varied from low class (94 %) to medium class (6 %). However, in the pre-monsoon season the percentage (%) of HPI classes ranged from low class (79 %), medium class (18 %) and 3 % of groundwater samples belong to high class.

In conclusion, the concentrations of dissolved metals (Al, As, Ba, Cr, Cu, Fe, Mn, Ni, Se and Zn) and HPI values in the groundwater of the West Bokaro coalfield area, demonstrated great seasonality. Seasonal variations in the HPI values showed that 21 % samples in the pre-monsoon season and 6 % samples in the post-monsoon season are not suitable for direct consumption. High HPI were observed at one location (Hesagara) near to mining area. All the other locations fall under low to medium classes of HPI in both seasons. Concentrations of the Al, Fe, Mn, and Ni are exceeding the desirable limits in many groundwater samples in both seasons and require suitable treatment before its utilization. The higher values of metals in the groundwater samples are attributed to the geological and mining sources.

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References

Ammann AA, Michalke B, Schramel P (2002) Speciation of heavy metals in environmental water by ion chromatography coupled to ICP-MS. Anal Bioanal Chem 372(3):448–452

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

BIS (2003) Indian standard drinking water specifications IS 10500:1991, edition 2.2 (2003–2009). Bureau of Indian Standards, New Delhi

Chandra S, Singh PK, Tiwari AK, Panigrahy B, Kumar A (2015) Evaluation of hydrogeological factor and their relationship with seasonal water table fluctuation in Dhanbad district, Jharkhand, India. ISH J Hydraul Eng 21(2):193–206

Dhakate R, Singh VS (2008) Heavy metal contamination in groundwater due to mining activities in Sukinda valley, Orissa-a case studies. J Geogr Reg Plan 1(4):58–67

Edet AE, Offiong OE (2002) Evaluation of water quality pollution indices for heavy metal contamination monitoring. A study case from Akpabuyo–Odukpani area, Lower Cross River Basin (southeastern Nigeria). Geo J 57:295–304

Gautam SK, Maharana C, Sharma D, Singh AK, Tripathi JK, Singh SK (2015) Evaluation of groundwater quality in the Chotanagpur plateau region of the Subarnarekha river basin, Jharkhand State, India. Sustain Water Qual Ecol 6:57–74

Giri S, Mahato MK, Singh G, Jha VN (2012) Risk assessment due to intake of heavy metals through the ingestion of groundwater around two proposed uranium mining areas in Jharkhand, India. Environ Monit Assess 184(3):1351–1358

Heyden CJ, New MG (2004) Groundwater pollution on the Zambian Copperbelt: deciphering the source and the risk. Sci Total Environ 327:17–30

Jahanshahi R, Zare M (2015) Assessment of heavy metals pollution in groundwater of Golgohar iron ore mine area, Iran. Environ Earth Sci 74(1):505–520

Karbassi AR, Nouri J, Ayaz GO (2007) Flocculation of trace metals during mixing of Talar river water with Caspian Seawater. Int J Environ Res 1(1):66–73

Krishan G, Singh S, Singh RP, Ghosh NC (2016) Water quality index of groundwater in Haridwar district, Uttarakhand, India. Water Energy Int 58(10):55–58

Kumar S, Bharti VK, Singh KB, Singh TN (2010) Quality assessment of potable water in the town of Kolasib, Mizoram (India). Environ Earth Sci 61(1):115–121

Kumar PS, Delson PD, Babu PT (2012) Appraisal of heavy metals in groundwater in Chennai city using a HPI model. Bull Environ Contam Toxicol 89(4):793–798

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

Mohan SV, Nithila P, Reddy SJ (1996) Estimation of heavy metal in drinking water and development of heavy metal pollution index. J Environ Sci Health A 31(2):283–289

Nouri J, Mahvi AH, Jahed GR, Babaei AA (2008) Regional distribution pattern of groundwater heavy metals resulting from agricultural activities. Environ Geol 55(6):1337–1343

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

Prasanna MV, Nagarajan R, Chidambaram S, Elayaraja A (2012) Assessment of metals distribution and microbial contamination at selected Lake waters in and around Miri city, East Malaysia. Bull Environ Contam Toxicol 89(3):507–511

Ramesh R, Purvaja GR, Raveendra V (1995) The problem of groundwater pollution: a case study from Madras city, India. Man's influence on freshwater ecosystems and water use (Proceedings of a Boulder symposium, July 1995). IAHS publication no. 230, pp 147–157

Selvam S, Venkatramanan S, Singaraja C (2015) A GIS-based assessment of water quality pollution indices for heavy metal contamination in Tuticorin Corporation, Tamilnadu, India. Arab J Geosci 8(12):10611–10623

Senapaty A, Behera P (2012) Concentration and distribution of trace elements in different coal seams of the Talcher coalfield, Odisha. Int J Earth Sci Eng 5(05):80–87

Simeonov V, Stratis JA, Samara C, Zachariadis G, Voutsa D, Anthemidis A (2003) Assessment of the surface water quality in northern Greece. Water Res 37:4119–4124

Singaraja C, Chidambaram S, Srinivasamoorthy K, Anandhan P, Selvam S (2015) A study on assessment of credible sources of heavy metal pollution vulnerability in groundwater of Thoothukudi districts, Tamilnadu, India. Water Qual Expo Health 7(4):459–467

Singh G, Kamal RK (2015) Assessment of groundwater quality in the mining areas of Goa, India. Indian J Sci Tech 8(6):588–595

Singh AK, Raj B, Tiwari AK, Mahato MK (2013a) Evaluation of hydrogeochemical processes and groundwater quality in the Jhansi district of Bundelkhand region, India. Environ Earth Sci 70(3):1225–1247

Singh PK, Tiwari AK, Mahato MK (2013b) Qualitative assessment of surface water of West Bokaro Coalfield, Jharkhand by using water quality index method. Int J ChemTech Res 5(5):2351–2356

Singh PK, Tiwari AK, Panigarhy BP, Mahato MK (2013c) Water quality indices used for water resources vulnerability assessment using GIS technique: a review. Int J Earth Sci Eng 6(6–1):1594–1600

Singh P, Tiwari AK, Singh PK (2014) Hydrochemical characteristic and quality assessment of groundwater of Ranchi township area, Jharkhand, India. Curr World Environ 9(3):804–813

Singh S, Ghosh NC, Krishan G, Galkate R, Thomas T, Jaiswal RK (2015) Development of an overall water quality index (OWQI) for surface water in Indian context. Curr World Environ 10(3):813–822

Tiwari AK, Singh AK (2014) Hydrogeochemical investigation and groundwater quality assessment of Pratapgarh district, Uttar Pradesh. J Geol Soc India 83(3):329–343

Tiwari AK, De Maio M, Singh PK, Mahato MK (2015) Evaluation of surface water quality by using GIS and a heavy metal pollution index (HPI) model in a coal mining area, India. Bull Environ Contam Toxicol 95:304–310

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

USEPA (2009) National primary drinking water regulations. Federal register, EPA816-F-09-004. Environmental Protection Agency, Washington

Varghese J, Jaya DS (2014) Metal pollution of groundwater in the vicinity of Valiathura sewage farm in Kerala, South India. Bull Environ Contam Toxicol 93(6):694–698

Vega M, Pardo R, Barrado E, Deban L (1998) Assessment of seasonal and polluting effects on the quality of river water by exploratory data analysis. Water Res 32:3581–3592

Verma AK, Singh TN (2013) Prediction of water quality from simple field parameters. Environ Earth Sci 69(3):821–829

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

WHO (2006) Guidelines for drinking-water quality, 3rd edn. World Health Organization, Geneva

Yadav KK, Gupta N, Kumar V, Sharma S, Arya S (2015) Water quality assessment of Pahuj River using water quality index at Unnao Balaji, MP, India. Int J Sci Basic Appl Res 19(1):241–250

Yankey RK, Fianko JR, Osae S, Ahialey EK, Duncan AE, Essuman DK, Bentum JK (2013) Evaluation of heavy metal pollution index of groundwater in the Tarkwa minning area, Ghana. Elixir Pollut 54:12663–12667