

Identification of artificial groundwater recharging zone using a GIS-based fuzzy logic approach: a case study in a coal mine area of the Damodar Valley, India

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Received: 24 July 2016 / Accepted: 25 July 2017 / Published online: 4 August 2017
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Abstract The West Bokaro coalfield is a richest coal-mining belt in the Damodar Valley, India. The extensive mining of the area has resulted in disruption of the groundwater availability in terms of both quantity and quality. This has led to a drinking water crisis, especially during the pre-monsoon period in the West Bokaro coalfield area. The characterization of the hydrogeological system and the artificial recharging of the aquifers might help to better manage the problem of the groundwater-level depletion. For this purpose, seven important hydrogeological factors (water depth, slope, drainage, soil, infiltration, lithology, and landuse) have been considered to define the most suitable locations for artificial groundwater recharging in the mining area. Different thematic maps were prepared from existing maps and data sets, remote-sensing images, and field investigations for identification of the most suitable locations for artificial recharge. Thematic layers for these parameters were prepared, classified, weighted, and integrated into a geographic information system (GIS) environment by means of fuzzy logic. The results of the study indicate that about 29 and 31% of the area are very suitable and suitable for recharging purposes in the West Bokaro coalfield. However, the rest of the area is moderate to unsuitable for recharging due to the ongoing mining and related activities in the study area. The

groundwater recharging map of the study area was validated with measured electrical conductivity (EC) values in the groundwater, and it indicated that validation can be accepted for the identification of groundwater recharging sites. These findings are providing useful information for the proper planning and sustainable management of the groundwater resources in the study area.

Keywords West Bokaro coalfield · Remote sensing · Artificial recharging · Results validation · Mining activities · Groundwater management

Introduction

Groundwater is considered as one of the most basic and precious needs for the survival of mankind to fulfill our basic necessities of life. In India, more than 90% of the rural and 30% of the urban populations depend on groundwater for drinking and domestic requirements (Reddy et al. 1996). Water scarcity and over-exploitation of groundwater resources are common in several parts of India (Garg and Hassan 2007; Tiwari et al. 2009; Tiwari and Singh 2014). The principal cities and towns in India are facing serious problems related to groundwater-level depletion and groundwater quality deterioration (CGWB 2000, 2001; Gagan et al. 2016; Gautam et al. 2015; Krishan et al. 2014; Kumar et al. 2010; Raju et al. 2011; Rodell et al. 2009; Verma and Singh 2013; Verma et al. 2016; Yadav et al. 2012). The decreasing water level and the adverse impact of industrial and agricultural activities, mining, urbanization, and global climate change are increasing the pressure on groundwater resources. Therefore, groundwater management has become a priority in the field of water resource research.

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A solution to the problem of groundwater-level depletion is the artificial recharging of the aquifers. A number of researchers have written about the groundwater-level exploitation in India and the need for artificial recharge of groundwater aquifers (Chowdhury et al. 2010; Krishnamurthy et al. 2000; Muthukrishnan et al. 2013). For developing sustainable environment management, the application of remote sensing (RS) data, ancillary data, and field observation data implemented in a geographic information system (GIS) environment is an essential technique.

On the one hand, remote sensing is one of the main sources of information about surface features related to groundwater resources management (Faurt et al. 1991; Hinton 1996; Jha et al. 2007). On the other hand, a GIS is a powerful tool for handling spatial data in many areas and for quick strategic decision making by a wide range of users, such as local authorities, as it includes both hydrogeological and environmental parameters (Stafford 1991; Singh et al. 2013). As groundwater is dynamic and interdisciplinary in nature, an integrated approach of RS and GIS techniques is very useful in groundwater resource management (Chowdhury et al. 2010). Recently, around the world, several researchers have used RS and GIS techniques for the evaluation of potential groundwater zones (Basavarajappa et al. 2013; Chenini et al. 2010; Dinesh Kumar et al. 2007; Machiwal et al. 2011; Machiwal and Singh, 2015; Magesh et al. 2012; Sener et al. 2005; Shaban et al. 2006; Yeh et al. 2009). In particular, a number of researchers have studied groundwater protection zones and the groundwater level in Jharkhand state in India with the help of RS and GIS techniques (Chandra et al.

2015; Chowdary et al. 2009; Kumar and Kumar 2010; Rai et al. 2005; Sharma and Kujur 2012; Srivastava et al. 2012).

Proper planning and sustainable management of the groundwater resources are essential, because mining and related activities can damage the aquifer and reduce the available groundwater supplies. The West Bokaro coalfield is deeply affected by the mining industry and faces an acute shortage of potable surface water, so people are very much dependent on the groundwater resources. Thus, the main objective of the present study is to identify suitable groundwater recharge sites in the West Bokaro coalfield of Jharkhand state using RS and a GIS-based fuzzy logic model.

Study area

The study area is the West Bokaro coal-mining region, which covers 207 km². It is located in Ramgarh district of Jharkhand, India. The West Bokaro coalfield stretches between 23°41' and 23°52' N latitude and 85°24' to 85°41' E longitude, as shown in Fig. 1. It has an extent of 65 km from East to West and between 10 and 16 km from North to South. The Bokaro West and Bokaro East are two subdivisions of the field separated almost in the middle by the Lugu Hill (height 960.9 m), which has an area of about 25 km². 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 an elevation between 229 and 350 m and 36.6% between 350 and 400 m and a small area, i.e., 1.6%, above 400 m (Tiwari

Fig. 1 Sampling location map of the West Bokaro coalfield area

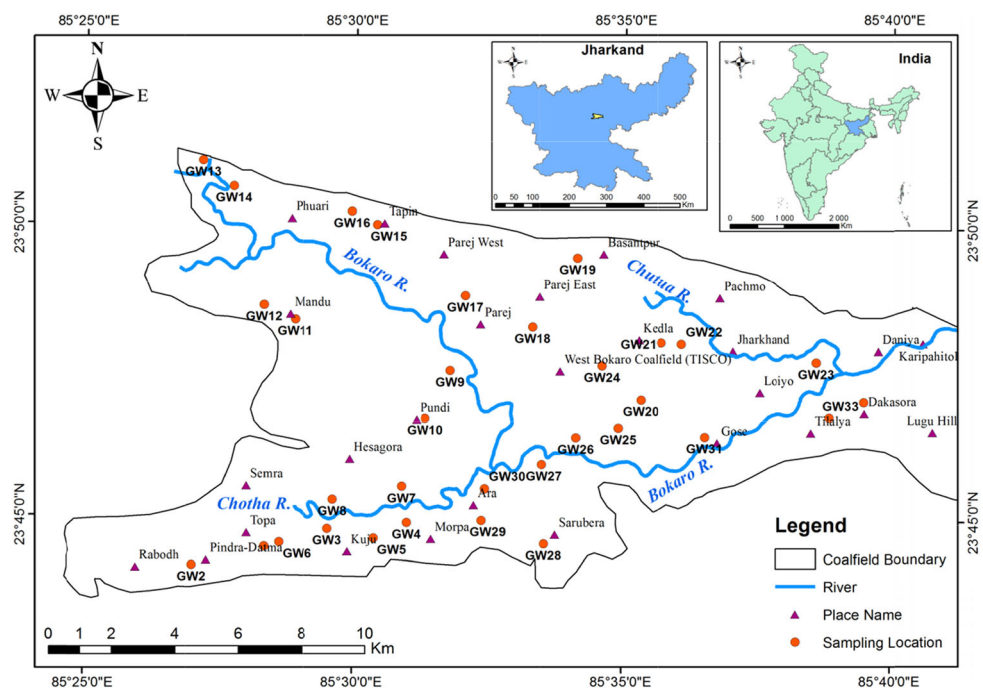
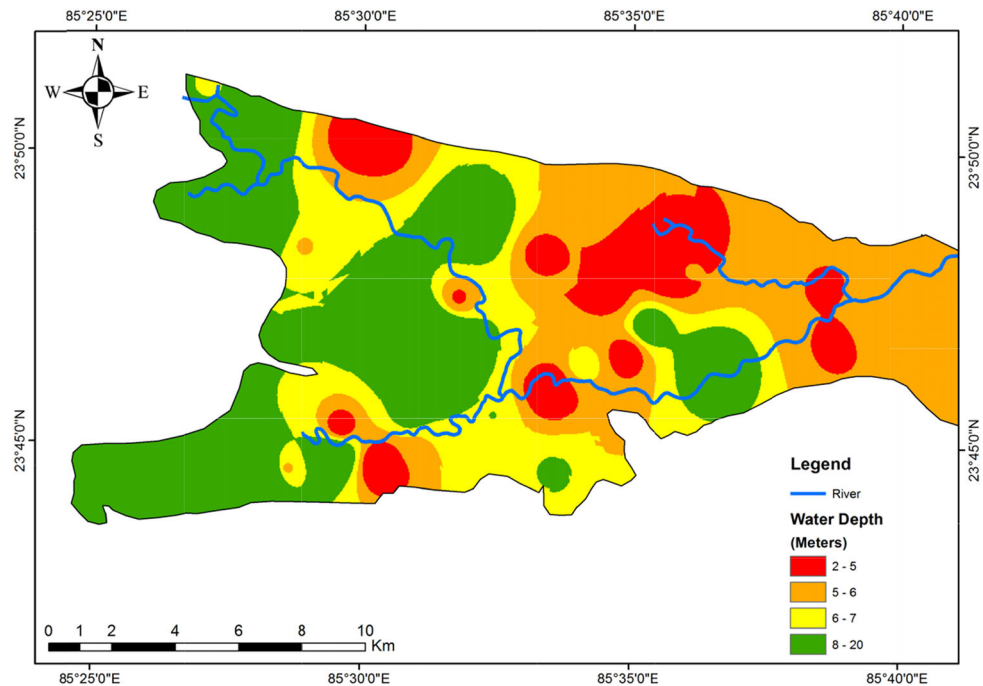


Table 1 Classes of the seven hydrogeological factors (water depth, slope, drainage, soil, infiltration, lithology, and landuse)

Suitable classes	Depth to water table (m)	Area km ²	Area (%)
Water depth of the study area			
Very suitable	8–20	76	37
Suitable	6–7	41	20
Moderate suitable	5–6	63	30
Unsuitable	2–5	27	13
Suitability classes	Slope class (%)	Area km ²	Area (%)
Slope of the study area			
Very suitable	0–2	37	17.8
Suitable	3–4	69	33.3
Moderate suitable	5–7	66	31.9
Unsuitable	8–67	35	17
Suitable classes	Drainage density (km/kmq)	Area km ²	Area %
Drainage density of the study area			
Very suitable	0–1	50	24.2
Suitable	1–1.5	51	24.6
Moderate suitable	1.5–2	53	25.6
Unsuitable	>2	53	25.6
Suitable classes	Soil type	Area km ²	Area %
Soil type of the study area			
Very suitable	Sandy loamy	16	8
Suitable	Loamy	58	28
Moderate suitable	Fine	23	11
Unsuitable	Fine loamy	110	53
Suitable classes	Infiltration (mm/year)	Area km ²	Area (%)
Infiltration rate of the study area			
Very suitable	263–460	23	11.2
Suitable	197–263	110	53.1
Moderate suitable	26–197	57	27.5
Unsuitable	0–26	17	8.2
Suitable classes	Lithology	Area km ²	Area %
Lithology of the study area			
Very suitable	Sandstone	168	81
Suitable	Metamorphic	27	13
Moderate suitable	Red clay	4	2
Unsuitable	Shale	8	4
Suitable classes	Landuse	Area km ²	Area %
Landuse type of the study area			
Very suitable	Water bodies	4.8	2
Suitable	Cultivated land	80	39
Moderate suitable	Forest and grassland	105.6	51
Unsuitable	Mining	16.6	8

Fig. 2 Water depth class map of the West Bokaro coalfield



et al. 2015). The West Bokaro coalfield is drained by the Bokaro River passing through the central part of the coal-mining area with the easterly flow. The Chutua 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

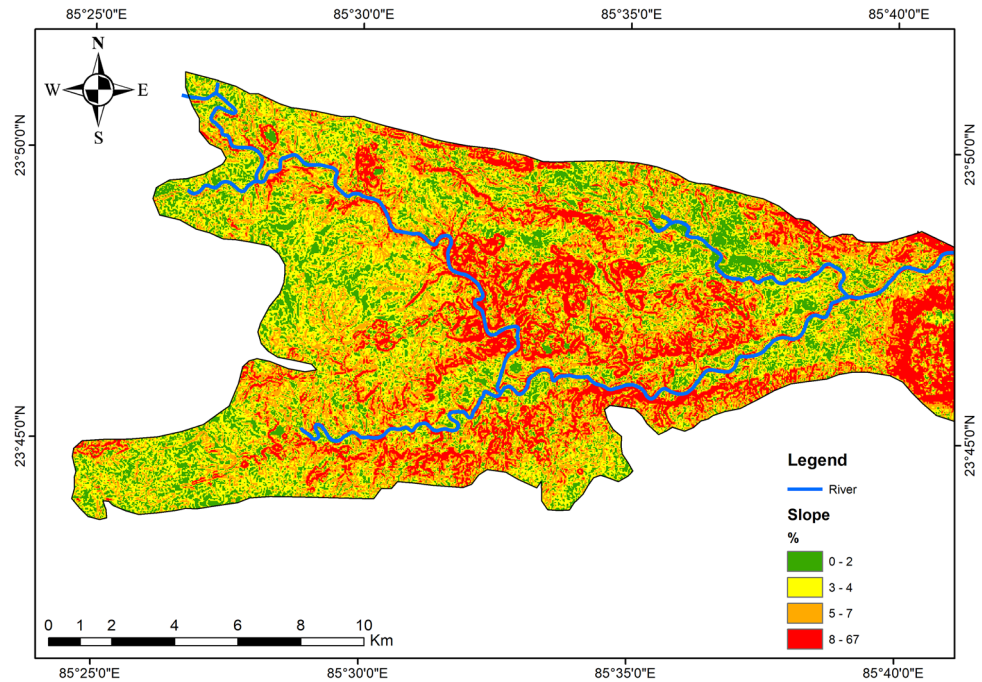
The West Bokaro coalfield area has a tropical climate and is characterized by a very hot pre-monsoon and cold post-monsoon season. May and mid-June represent the peak of pre-monsoon season with an average maximum temperature of 44 °C. Summer is very hot and dusty, but the nights are generally pleasant (Tiwari et al. 2015). Winter (November to February) is cold and minimum temperatures reach 4 °C. In the area, rainfall mostly occurs in the monsoon period, June to September. Meagre rainfall due to the conventional thunderstorms occurs during the months of April and May (http://ietd.inflibnet.ac.in:8080/jspui/bitstream/10603/16830/9/09_chapter%202.pdf). Occasional winter rainfall is associated with western disturbances. During the monsoon months, depressions are formed in the Bay of Bengal. The maximum variability of rainfall is recorded during the months of July and August. It has been observed that the average annual rainfall fluctuates in a range between 927 and 1588 mm. The average annual rainfall is 1418 mm and more than 85% of annual rainfall occurs during the four monsoon months (June to

September) (Tiwari et al. 2015). In the present study, we have taken the average rainfall of the years 2012 and 2013.

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 uncomfortably on basement rocks. The geological formation of the study area consists of Barakar Formation, Barren Measures, Mahadeva, Metamorphics, Panchet, Raniganj, and Talchir Formation. The coalfield exhibits a twin synformal structure known as Northern and Southern synform, separated by a hill which maintains 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 for the sub-basinal structures, as in the Tapin and Parej blocks. The coalfield has numerous strikes and oblique faults. The row of these faults varies from a few meters to more than 400 m. Igneous rocks present 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 an NE–SW direction.

Fig. 3 Slope class map of the West Bokaro coalfield



Hydrology and hydrogeology

The environmental setting and topography of the area are generally sloping towards east to south-east. 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 Chotanagpur 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 0.25 and 14.25 m from the ground level.

Materials and methods

Seven hydrogeological factors, viz., water depth, slope, drainage, soil, infiltration, lithology, and landuse, have been considered to define the most suitable locations for artificial groundwater recharge in the mining area. Using thematic maps obtained from existing maps and data sets, remote-sensing images, and field investigations, thematic

layers for these hydrogeological factors were prepared, classified, weighted, and integrated into a GIS-based fuzzy logic environment.

The Survey of India (SOI) topographical maps were georeferenced and projected to the UTM Datum: WGS—84 Zone—45 N coordinate system. These SOI topographical maps were digitized in the ArcMap GIS 10.2 software to generate the base map of the West Bokaro coalfield (Fig. 1).

In the study area, 33 wells were selected to monitor the groundwater level. The data set used in this work covers one pre-monsoon cycle from May 2013 to May 2014. The water depth was measured using a sensor-based water-level recorder. The water depth map was prepared using the IDW interpolation tool on the ESRI's Arc GIS 10.2 software. The area under study was divided into four classes based on field experience (Table 1; Fig. 2).

The occurrence and the movement of groundwater are strongly governed by the slope. Therefore, this parameter can be considered an important factor in runoff flows and potential infiltration. The terrain slope can be measured in degree from horizontal (0–90) or percent slope 0–100. The water velocity is directly related to the angle of slope and depth. The Cartosat Digital Elevation Model (DEM 2013) of the 30-m resolution was procured from the BHUVAN portal of the NRSC (National Remote Sensing Centre) and was transformed into a GIS database. The slope map is derived from the DEM using the Spatial Analyst tool available in ArcGIS. On the slope map, the slopes are

Fig. 4 Drainage density class map of the West Bokaro coalfield

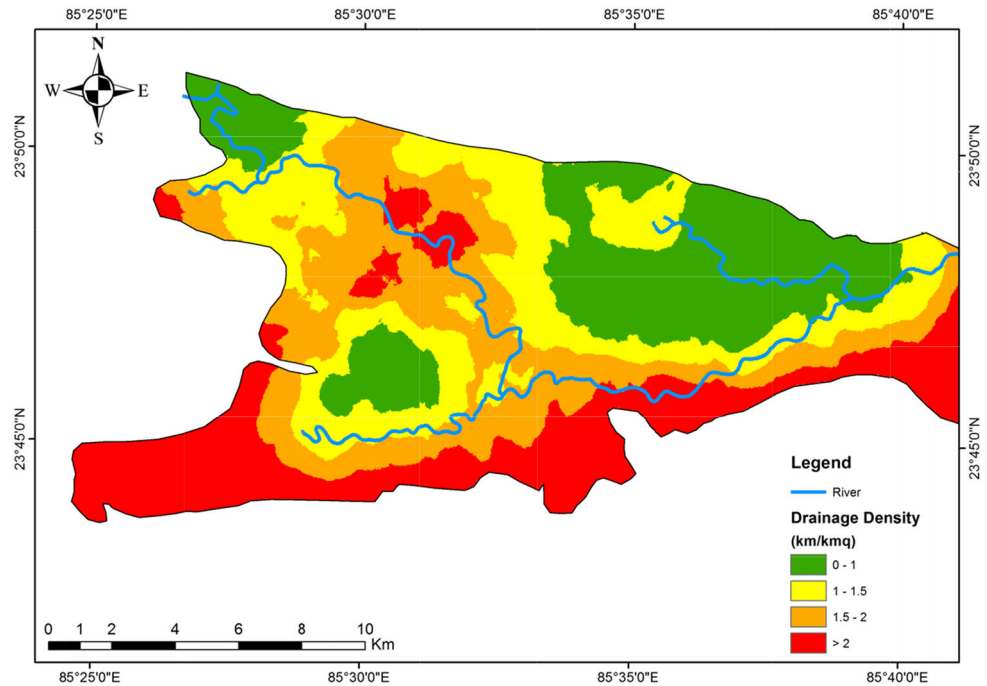
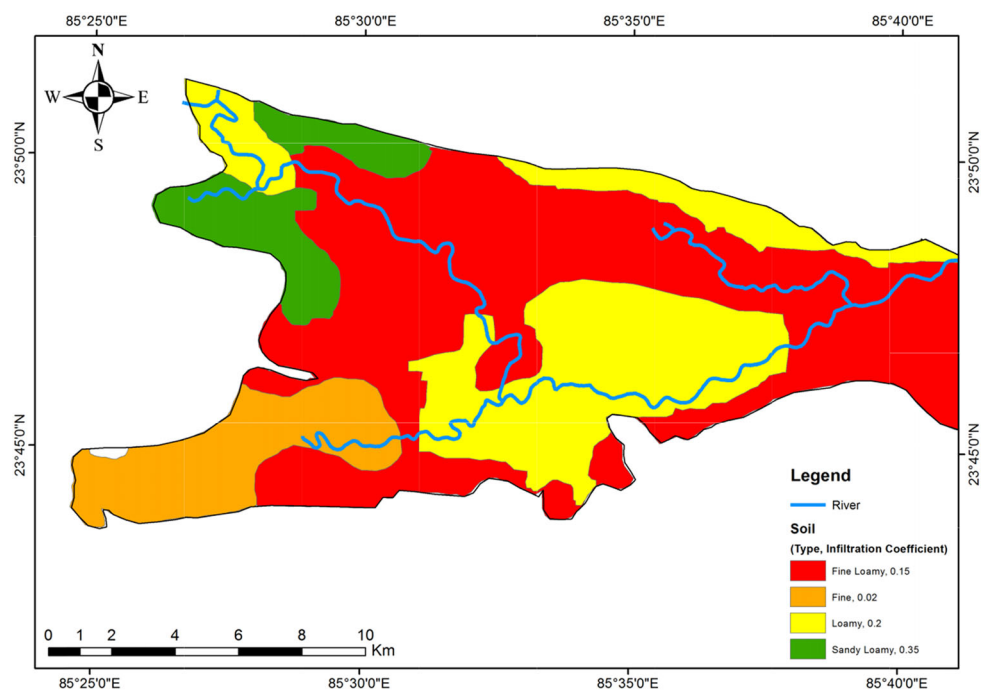


Fig. 5 Soil class map of the West Bokaro coalfield

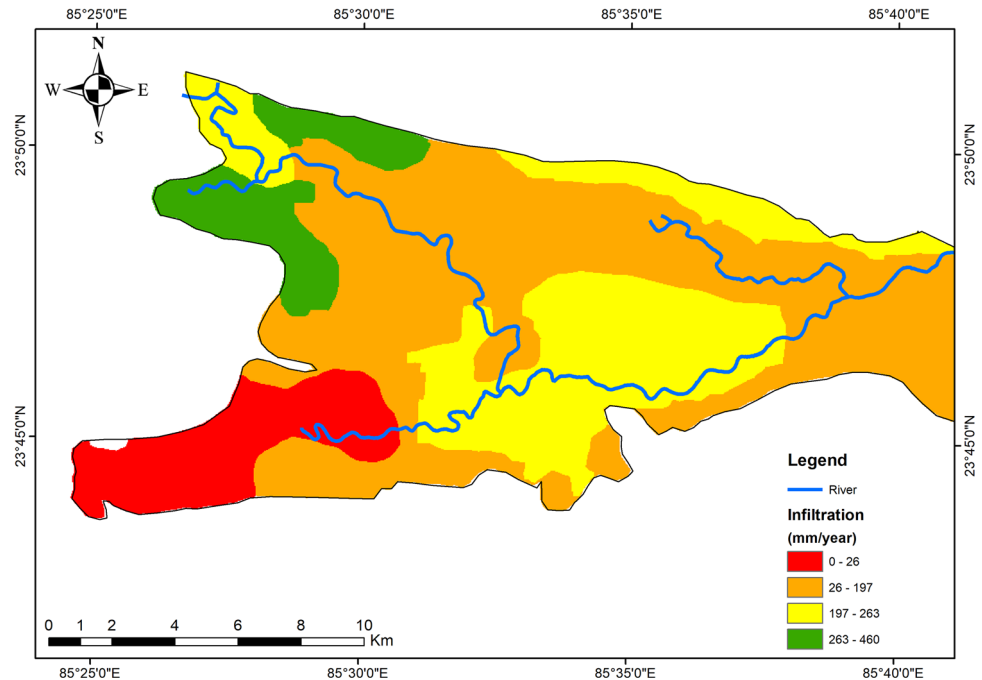


classified into four classes according to Ghayoumian et al. (2007) (Table 1; Fig. 3).

The drainage parameter causes variations in the recharging of the aquifers. The spatial arrangement of streams and the flow direction based on the DEM define a particular structure which is called drainage pattern. IRS

LISS III images of the study area were obtained from the National Remote-Sensing Centre (NRSC, India) and they have been used to extract the drainage map of the study area in a GIS environment. The drainage density map is calculating the segment length of the drainage system per square kilometer of the watershed area related to each

Fig. 6 Infiltration class map of the West Bokaro coalfield



segment. The raster obtained has been reclassified in four classes (Table 1; Fig. 4).

Soil map of the study area was obtained from the State Agriculture Management and Extension Training Institute (SAMETI), Jharkhand and digitized in GIS environment. There are four types of soil present in the study area, i.e., sandy loamy, loamy, fine loamy, fine soil with loamy surface texture and moderate erosion, and fine loamy soil on very gently sloping land with loamy surface texture. The most of the study area (about 110 km²) is covered by fine loamy soil and the rest of the 58 km² 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 km², respectively. The area under study was divided into four classes on the basis of porosity of soil (Freeze and Cherry 1979) (Table 1; Fig. 5).

Infiltration is the process by which water on the ground surface enters the soil. For calculation of infiltration rate of the area, rainfall data were taken from the weather station located at the Kuju area office of the West Bokaro coalfield, India. Infiltration values were determined according to texture permeability relationships (Civita and De Maio 2000). The infiltration map is classified into four classes according to FAO (1979) and Ghayoumian et al. (2007) (Table 1; Fig. 6).

The lithological details of the study area were collected from the lithology of different mines of Central Coalfield Limited (CCL), India and generated a lithology map in GIS environment. The study area has mostly covers by sandstone. The lithology map is classified into four different

classes on the basis of permeability (Aller et al. 1987) (Table 1; Fig. 7).

The landuse classification map of the coalfield area was obtained from Globalland30 (National Geometrics Centre of China). Remote-sensing images were used to generate a landuse map of the study area in a GIS environment to determine the relationships between geomorphological units. The landuse map is classified into four different classes (Fig. 8). The area covered by each landuse type is shown in Table 1.

There are several methods to develop thematic layers. In this study, fuzzy logic is used to combine the different classified layers in a GIS environment. Fuzzy logic is an integrated approach to computing based on “degrees of truth” rather than the usual “true or false” (1 or 0). Membership of a fuzzy set, however, is expressed on a continuous scale from 1 (full membership) to 0 (full non-membership). Each map of single classes may be defined according to its degree of membership. The fuzzy membership values could be associated with the classes of any map in an attribute table. Fuzzy membership values must lie in the range (0, 1), but there are no useful restraints on the selection of fuzzy membership values (Bonham-Carter 1996). In the fuzzy membership functions with two or more maps in the same set, a variety of operations could be carried out to combine the membership values together. The combination rules of a variety were disused by Zimmermann and Zysno (1980). According to An et al. (1991), there were five fuzzy operators, namely, fuzzy AND, fuzzy OR, fuzzy algebraic product, fuzzy algebraic sum, and

Fig. 7 Lithology class map of the West Bokaro coalfield

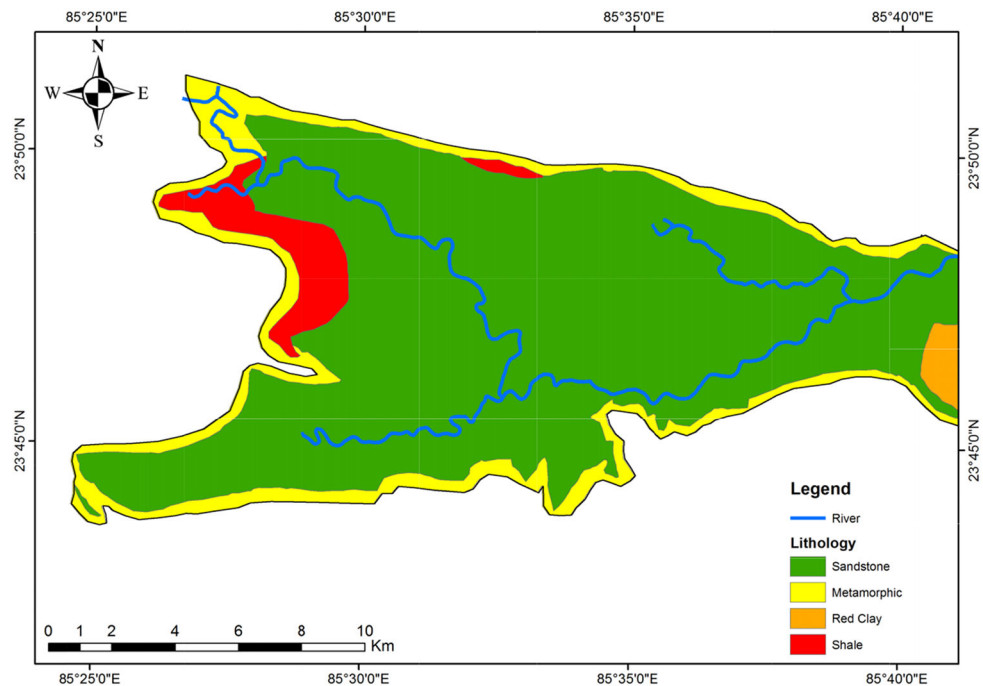
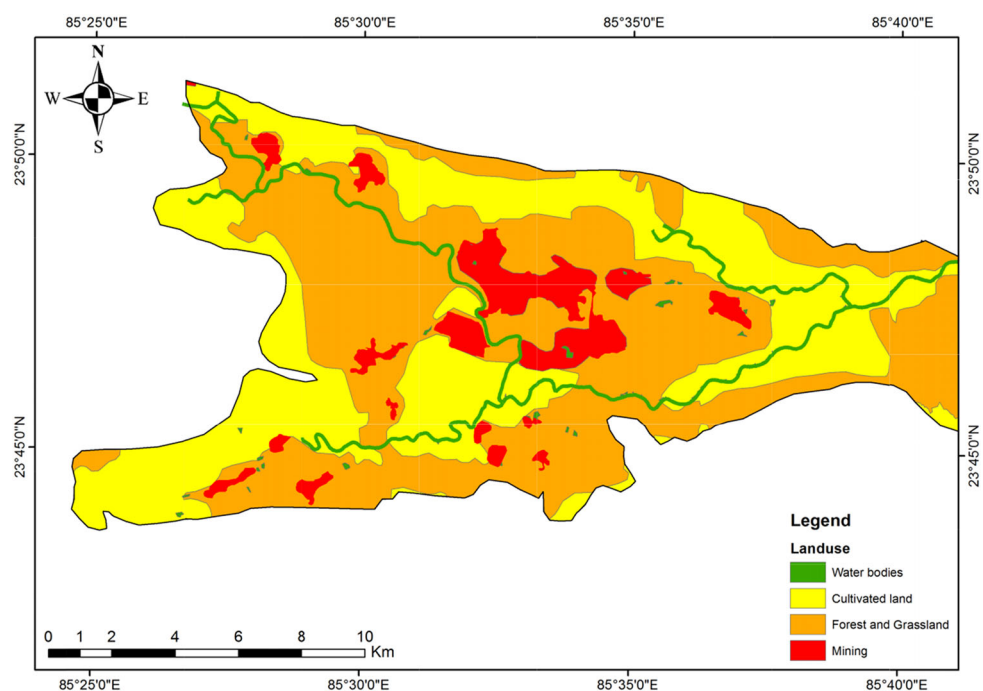


Fig. 8 Landuse class map of the West Bokaro coalfield



fuzzy gamma operator. In fuzzy algebraic products, the combined membership function is defined as

$$\mu_{\text{combination}} = \prod_{i=1}^n \mu_i$$

where, μ_i is the fuzzy membership function for the i th map, and $i = 1, 2, 3, \dots, n$ maps are to be combined. The

combined fuzzy membership values tend to be very small with this operator, due to the effect of multiplying several numbers less than 1. The output is always smaller than, or equal to the smallest contributing membership value, and it is, therefore, 'decreasing' (Bonham-Carter 1996).

In site selection for artificial recharge, the fuzzy algebraic product operator can be an appropriate combination

Fig. 9 Areas suitable for artificial groundwater recharging in the West Bokaro coalfield

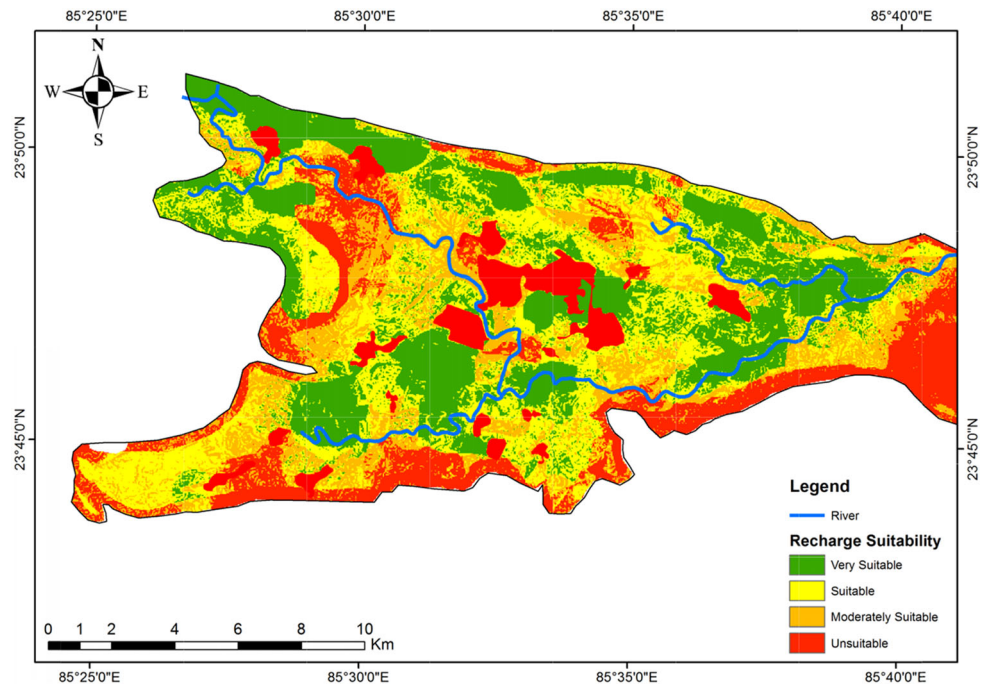


Table 2 Recharge suitability

Suitability	Area km ²	Area %
Very suitable	60	29
Suitable	64	31
Moderate suitable	45	22
Unsuitable	38	18

operator, because at each location, the combined fuzzy membership value of the thematic maps to illustrate water depth, slope, drainage, soil, infiltration, lithology and landuse, and their characteristics is obtained. In this research, the fuzzy algebraic product operator was used because of its high sensitivity for specifying artificial recharge areas. The artificial groundwater recharge suitability map using a GIS-based fuzzy model is presented in Fig. 9.

Results and discussion

On the basis of integrated and weighted analyses of the various thematic maps (water depth, slope, drainage, soil, infiltration, lithology, and landuse) applied in the GIS-based fuzzy logic models, the most suitable artificial recharging areas in the West Bokaro coalfield were identified (Fig. 9).

Integrating thematic layers using the fuzzy logic indicated that 29% of the area was very suitable, and 31% of the area was suitable for the artificial recharge of the groundwater. However, 22% of the area was moderate

suitable and 18% area fell into the unsuitable for groundwater recharging due to ongoing mining and related activities in the study area (Fig. 9; Table 2).

The groundwater recharging map was validated with the measured electrical conductivity (EC) values in the groundwater of the study area. Groundwater samples were collected from 33 wells in the West Bokaro coalfield area and value of EC was measured in the field using a Consort C831 portable conductivity meter. Electrical conductivity (EC) varied from 170 to 1734 $\mu\text{S cm}^{-1}$ with an average value of 895 $\mu\text{S cm}^{-1}$ in the groundwater of the area. Figure 10 clearly indicates that the trends of EC values and recharging maps were matched closely in most of the occasions, except in a few places. Figure 10 clearly indicates that the high EC values of the groundwater samples were lie in the moderate-to-unsuitable zone, except in a few places. It was also observed that the low EC values of the water samples stretched out in the very suitable to suitable recharging zone. This clearly indicates that the EC validation can be accepted for identification of the groundwater recharging sites.

This result suggested that a GIS-based fuzzy logic, as well as remote-sensing technique, has an important role to play in maintaining the proper balance between the groundwater quantity and its exploitation. Table 3 provides a comparison of the potential groundwater zone of the West Bokaro coalfield with other studies done by a number of researchers in Jharkhand state, India. Previous studies of Jharkhand (Kumar and Krishna 2016; Shekhar and Pandey 2015; Srivastava et al. 2012) have also reported that the hydrogeological factors in a GIS environment play an

Fig. 10 Electrical conductivity map for validation of recharge suitability of the West Bokaro coalfield

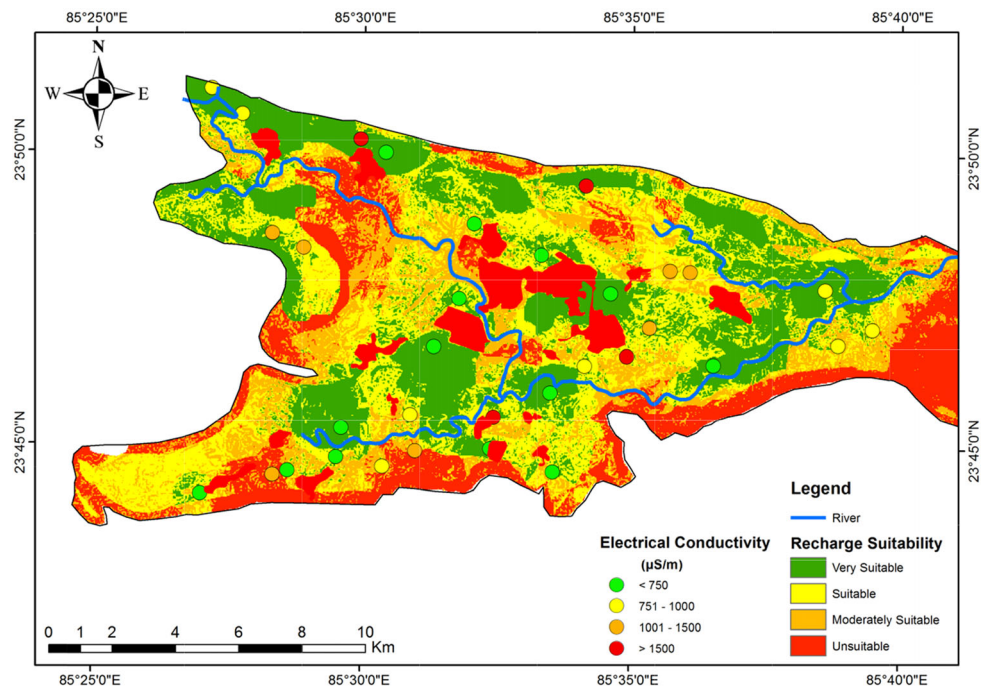


Table 3 Comparison of groundwater potential zone of the West Bokaro coalfield with other studies done in Jharkhand, India

S. no.	Name of place	Groundwater potential area (%)				References
		Very suitable	Suitable	Moderate suitable	Unsuitable	
1	Dhanbad	12	45	15	28	Srivastava et al. (2012)
2	Ramgarh	33.89	28.49	30.63	6.98	Kumar and Krishna (2016)
3	Palamu	11.6	13.27	36.89	38.23	Shekhar and Pandey (2015)
4	West Bokaro coalfield	29	31	22	18	Present study

important role in identifying suitable recharge areas for groundwater, as well as being a useful technique for future sustainable groundwater management. This comparison clearly indicates that our findings provide useful information for the proper planning and sustainable management of the groundwater resources in the area.

Conclusion

This study aimed to identify suitable artificial recharging sites in the West Bokaro coalfield using a GIS-based fuzzy logic. Satellite data proved to be very useful for ground surface studies, especially to obtain maps of current land-use, slope, and drainage. Integrated assessment of these thematic maps using a GIS-based-fuzzy logic model proved a suitable method to identify the best artificial recharge sites.

The results show that about 60% of the area was suitable for recharging purposes, while 40% of the area was moderate to unsuitable for groundwater recharging. This study highlights that the mining and related activities have an adverse effect on the groundwater potential in the study area. Thus, this study provided the most suitable artificial recharging sites in the study area, for the purpose of improving the groundwater level. This may be helpful in the future for the sustainable management of the water resources in these mining areas.

Acknowledgements The authors are grateful to the Director, Indian Institute of Technology (Indian School of Mines) Dhanbad, India for his kind support. One of the authors (Dr. Ashwani Kumar Tiwari) is grateful to ISM/MHRD/Government of India and European Commission (Erasmus Mundus AREaS + Program) for grant support. We are thankful to Central Coalfield Limited (CCL), India for their support. Our hearty thanks to the Reviewer and Editor-in-Chief for his valuable suggestions to improve the study in the present form.

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