

Characterization of groundwater potential and artificial recharge sites in Bokaro District, Jharkhand (India), using remote sensing and GIS-based techniques

Ipsita Satapathy¹ · Tajdarul H. Syed¹

Received: 26 May 2014 / Accepted: 27 April 2015 / Published online: 23 May 2015
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Abstract Anarchic use of groundwater for domestic and industrial purposes poses a major threat to the rapidly depleting groundwater resources of India. In the present study, an integrated remote sensing and GIS-based methodology is used for the mapping of groundwater potential zones and identification of suitable sites for artificial recharge in the Bokaro District of Jharkhand, India. The study area is classified into three different zones, namely ‘poor’, ‘moderate’ and ‘good’ in terms of its groundwater potential. Only small isolated patches in the eastern and central parts of the district have been identified to have good groundwater potential with a sustainable yield of 87.18 MCM (million cubic metres). The percent area coverage of regions with good groundwater potential is only ~5 %. The sustainable yield for areas characterized to have moderate groundwater potential is 962.11 MCM, while those with poor potential are estimated to be 53.31 MCM. Overall, the results show that 95 % of the study area have moderate to poor groundwater potentiality. Sensitivity analysis, using effective weight and variation index, reveals slope, drainage density and soil as the parameters with the greatest influence on the computation of groundwater potential index. The present study also focuses on the identification of suitable artificial recharge sites, using multi-criteria analysis technique, for augmenting the depleting groundwater reserves of the area. The results reveal that 84.95 % of the study area is either highly or moderately suited for artificial recharge, which is primarily

attributed to the predominance of favourable geology and geomorphologic features in the study area.

Keywords Groundwater potential · Artificial recharge · Hardrock aquifer · Remote sensing · Geographic information system · Multi-criteria analysis · SCS-CN runoff · Sensitivity analysis

Introduction

Groundwater is an important dynamic resource of freshwater supporting the needs of nearly 1.5–2.8 billion people globally (Morris et al. 2003). In India, groundwater meets the domestic requirement of more than 80 % of the rural population, besides fulfilling the requirements of ~50 % of irrigated agriculture (Kumar et al. 2005; Mall et al. 2006). Hence, the prospects of accessible groundwater play a major role in the socioeconomic development of a region. Dependency on groundwater, for food and energy production, to meet the requirements of a growing population and enhancement of human well-being has intensified over the years (Giordano 2009). Stress on groundwater resources is further compounded by physical alteration of landscape due to urban and industrial development (Pani-grahi et al. 1995). As a result, groundwater resources in major parts of India are confronted with the consequences of extreme overexploitation and associated unremitting decline in the water table (Rao 2003). The current decline in groundwater availability in India (Kumar et al. 2005) necessitates the formulation of sustainable groundwater management plan through proper assessment of the available resources.

Assessments of groundwater potential have been performed using several field-based techniques utilizing geo-

✉ Tajdarul H. Syed
tsyed.ismu@gmail.com

¹ Department of Applied Geology, Indian School of Mines, Dhanbad 826004, Jharkhand, India

electrical, seismic and basic well surveys (Rao and Jugran 2003; Sahu and Sahoo 2006). These methods are both cost and manpower intensive (Sander et al. 1996). In addition, basic well surveys are constrained by the number and distribution of observations wells, which are also typically unsystematic. An increasing realization of the limits of traditional surveys has led to the introduction of remote sensing and GIS-based techniques which are ideal for first-hand, holistic and regional assessment of groundwater potential. Remote sensing and GIS-based methods can be implemented over varied spatial extents and do not involve the utilization of an expensive array of instruments (Jha et al. 2007; Chowdary et al. 2009) and at times can also be merged with conventional field surveys (Kumar et al. 2009).

Integrated use of satellite image interpretation techniques and GIS are crucial to increase the accuracy of the results and to reduce the limitations of dependence on any single theme or layer of information (Mohanty and Behera 2010; Rao and Jugran 2003). As a result, these methods have been used extensively for groundwater potential mapping (e.g. Krishnamurthy et al. 1996; Pradeep 1998; Saraf and Chowdhury 1998; Sankar 2002; Khan and Moharana 2002). These methods have been successfully implemented in soft sediments (e.g. Shahid et al. 2000) as well as hard rock terrains in India (e.g. Khan and Moharana 2002; Prasad et al. 2008; Rekha et al. 2011). While the majority of these studies had focussed on the delineation of groundwater potential zones, others have concentrated on the identification of suitable sites for artificial recharge (Ghayoumian et al. 2005; Anbazhagan et al. 2005) and water-harvesting structures (Kumar et al. 2008).

Severe groundwater depletion can worsen social inequity by increasing water costs and limiting the access to individuals with deeper or larger capacity wells. This can provoke an expensive and inefficient cycle of well deepening with subsequent lowering of regional groundwater levels leading to severe, essentially irreversible, effects. Remediation through artificial recharge is often an important step for the restoration of depleting groundwater resources (Chowdhury et al. 2009; Sophiya and Syed 2013), amongst many others. However, it is extremely important to identify suitable sites, prior to artificial groundwater recharge initiatives, to make meaningful contribution towards the revival of groundwater resources. This is particularly relevant in the context of the study area, since the majority is underlain by crystalline rocks with negligible primary porosity. While the majority of the studies involving identification of suitable sites for artificial recharge have utilized weighted index overlay methods (Saraf and Chowdhury 1998; Agarwal et al. 2013b), some proposed the use of mathematical models such as analytical hierarchy process (Nagaraju et al. 2012), analytical network process (Agarwal et al. 2013a), SCS-CN method

(Agarwal et al. 2013b) and multi-criteria analysis (Hajkowicz and Collins 2006). Previously, the weighted overlay index method has been implemented in several key groundwater provinces in India (e.g. Srivastava and Bhattacharya 2006; Ravishankar and Mohan 2005).

The study area, Bokaro District, is one of the few highly industrialized regions in the state of Jharkhand. While regulations on the availability of freshwater for industrial purposes are likely to impede socioeconomic development, excessive groundwater withdrawal for industrial purposes can have serious human and ecosystem impacts. As a result, freshwater resource of the study area is continuously challenged by water scarcity issues attributed to over exploitation of groundwater (CGWB 2009). The lack of surface water bodies and groundwater loss due to mining-related activities add complexity to the already depleting groundwater resource of the study area. Therefore, groundwater potential mapping and aquifer replenishment through artificial recharge are imperative for long-term sustenance of groundwater resources in the study area. However, the groundwater resource potential of this study area has not been fully characterized. Here, we utilize multi-platform hydrogeologic data in a numerical ranking system, called weighted index overlay analysis, for the delineation of groundwater potential zones and identification of suitable sites for artificial recharge. This method takes into consideration the relative importance or contribution of each individual parameter and class belonging to each category of geospatial information (Nag 2005). Uniquely, the assessed groundwater potentiality of the study area is subjected to a sensitivity analysis to reveal the parameters with the greatest influence. Subsequently, these GIS-based assessments are corroborated with independent estimates of sustainable yield of groundwater and runoff estimates obtained from the SCS-CN model.

Study area

Bokaro District lies between the latitudes 23°24'27"N–23°57'24"N and longitudes 85°34'30"E–86°29'10"E, covering an area of 2861 sq km in the State of Jharkhand in India (Fig. 1). It is represented in Survey of India topographical map no. 73I/73E (1:250,000). It has eight administrative blocks, namely (1) Chas, (2) Gomia, (3) Nawadhi, (4) Bermo, (5) Peterwar, (6) Kasmar, (7) Jaridih and (8) Chandankiyari. The area experiences humid to subtropical climate with three distinct seasons that include summer, monsoon and winter. Monsoon sets in the middle of June and lasts till the end of September. July, August and September are the most humid months. The humidity during the winter season is about 60 %. Summer stretches from March to June during which the maximum temperature varies from 42 to

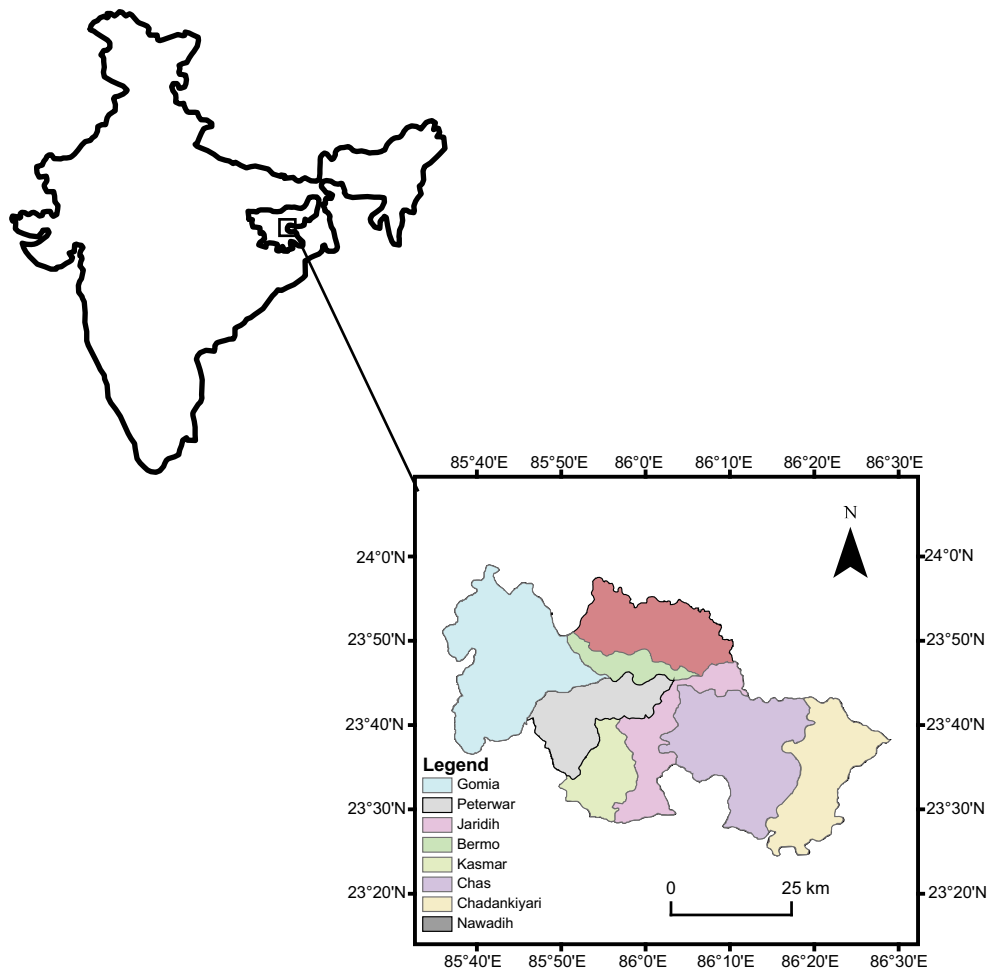


Fig. 1 Map of the study area along with the names of the blocks located within the District of Bokaro, Jharkhand, India

46 °C and humidity remains the lowest during these months. The average rainfall in the district is 1363.6 mm/year. Maximum rainfall occurs in the Chadankiyari block and the lowest in Kasmr and Nawadhi blocks.

Major parts of the study area are underlain by rocks such as granite and granite gneiss. Besides these rocks, quartzites, mica schists and phyllites are also found. The oldest rock of the area is unclassified meta-sedimentaries, which comprise quartzite and quartz schists. Three-fourths of the area is occupied by rocks of Chotanagpur granite gneiss. Coal, shale and sandstone deposits are found in parts of Bermo and Gomia blocks of the Bokaro District. A detailed geological succession of the study area is presented in Table 1.

Data and methodology

The data and methods used in the current study are discussed under two major sub-categories, which are also the primary objectives of this study. These are (1) delineation

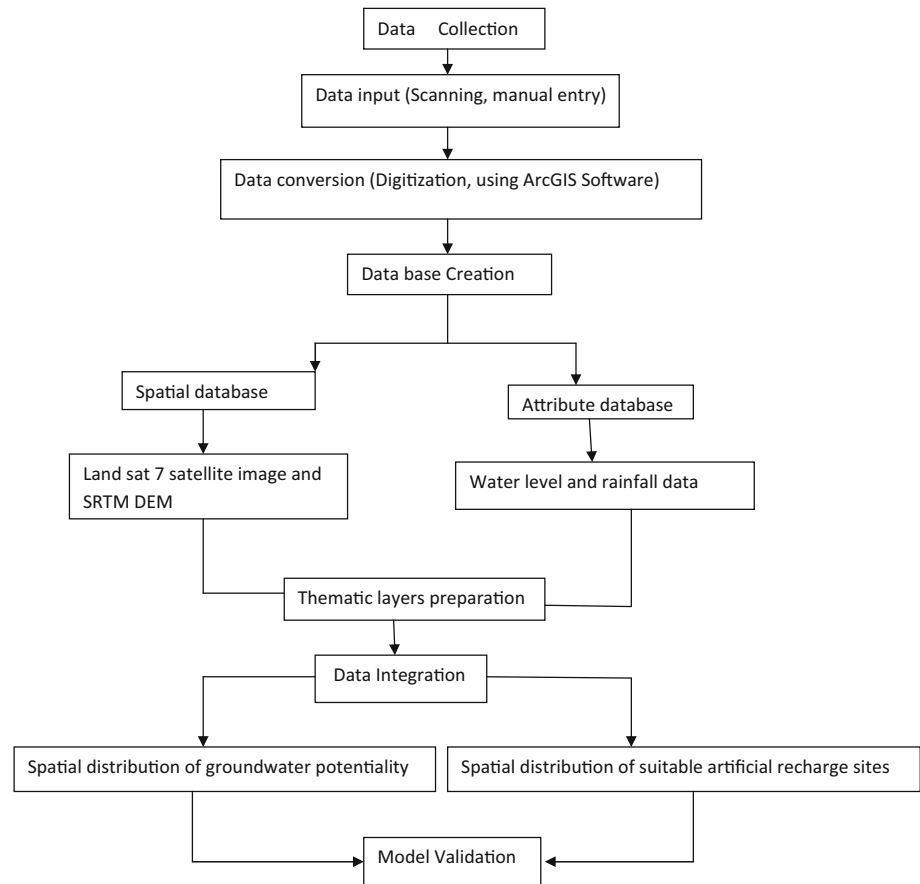
of groundwater potential zones and (2) identification of suitable sites for artificial recharge. The methodology is also summarized by a flowchart diagram shown in Fig. 2.

Identification of groundwater potential zones

The base map for this study is prepared from the Survey of India topographic sheet (No: 73E/73I at 1:250,000 scale). Additionally, Landsat Thematic Mapper (TM) satellite image of the study area, accessed from United States Geological Survey (<http://earthexplorer.usgs.gov>), has been extensively used for the generation of thematic maps/layers. Thematic layers of geomorphology, geology, lineament density, drainage density and land use/land cover maps are prepared using the Landsat TM satellite image utilizing the TM 1-3-5 and 1-2-3 band composites. The Landsat image is visually interpreted to map the geomorphologic units and land use/land cover with the help of standard characteristic image interpretation elements such as tone, texture, shape, size, pattern and association. The

Table 1 Geological succession of the study area

Age	Series	Lithology
Upper carboniferous to middle Jurassic	Gondwana supergroup	Sandstone, shale, grit, coal
Upper proterozoic		Amphibolite, epidiorite
Middle to upper proterozoic	Chotanagpur granite gneiss	Granite and granite gneiss, micaschist and phyllite
Lower to middle proterozoic	Unclassified metasediments	Quartzites

Fig. 2 Flowchart showing the methodology used in the present study

slope map and digital elevation model (DEM) of the area are prepared using the Shuttle Radar Topography Mission (SRTM) DEM (accessed from Consultative Group on International Agricultural Research (CGIAR) consortium for Spatial Information (CGIAR-CSI) (<http://srtm.csi.cgiar.org>)). Rainfall data used in this study is acquired from the Directorate of Economic and Statistics (Department of Planning and Development (<http://desjharkhand.nic.in>)) over a period of 10 years (2003–2013). The rainfall map is prepared using the inverse distance weighting (IDW) method. The hydrogeological soil map is prepared by using a base soil map of the study area obtained from the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP; <http://www.nbsslup.in/>). Further, the soil map is classified into four hydrogeological soil types (A, B,

C and D) according to the texture of soil and its infiltration capacity. All these thematic layers are ranked from 1 (very poor) to 5 (very good) depending on their suitability to store/transmit groundwater; these rank values are also illustrated in Table 2. For the weighted index overlay analysis, each of the individual thematic layers and its characteristic feature classes are assigned weights and ranks on the basis of their relative contribution towards the enhancement of groundwater potential; these are illustrated in Table 3. A quantitative evaluation of the different features in a given thematic layer is integrated to analyse the groundwater potential of the study area by computing the groundwater potential index (GWPI) using the weighted index overlay technique in a GIS platform following Eq. (1) (Mukherjee et al. 2012). Subsequently, the

Table 2 Rank assignments for features in a thematic layer based on their relative importance towards estimating groundwater potential and site suitability for artificial recharge

Rank	Condition for potential mapping	Condition for artificial recharge
1	Very poor	Unsuitable
2	Poor	Least suitable
3	Moderate	Moderately suitable
4	Good	Suitable
5	Very good	Most suitable

groundwater potential of the study area is classified into three classes, namely ‘poor’, ‘moderate’ and ‘good’, with GWPI values ranging from 2 to 4:

$$\begin{aligned}
 \text{GWPI} = & \text{Geo}_w\text{Geo}_r + \text{Geom}_w\text{Geom}_r + \text{Ld}_w\text{Ld}_r + \text{D}_w\text{D}_r \\
 & + \text{So}_w\text{So}_r + \text{Slo}_w\text{Slo}_r + \text{R}_w\text{R}_r + \text{LULC}_w\text{LULC}_r \\
 & + \text{DEM}_w\text{DEM}_r,
 \end{aligned}
 \tag{1}$$

where GWPI is the groundwater potential index; Geo the geology; Geom the geomorphology; D the drainage density; Ld the lineament density; Slo the slope; LULC the land use/land cover; R the rainfall; DEM the digital elevation model; the subscript r is rank of feature in a theme and w the weightage of themes. GWPI is a dimensionless entity.

Identification of suitable sites for artificial recharge

Artificial recharge is often an effective approach for replenishing the depleting groundwater resources. However, the effectiveness of initiating artificial recharge of groundwater is primarily dependent on hydrological and geological factors that are interrelated and spatially heterogeneous. Hence, it is extremely important to identify suitable sites before undertaking any major artificial recharge initiatives. Hence, identification of suitable sites for application of appropriate artificial recharge techniques is critical for effective recharge of the aquifer.

In this study, identification of suitable sites for artificial recharge is carried out by taking into consideration thematic maps of geomorphology, geology, slope and land use/land cover. Each class of feature identified in the individual layers are assigned rating values on a scale of 1 (Unsuitable) to 5 (Most suitable) based on their contribution towards the suitability for artificial recharge of groundwater (Table 2). Subsequently, an integration of the information contained in each of the layers and their respective classes is obtained by using the weighted index overlay method (Saraf and Chowdhury 1998) for the identification of sites suitable for artificial recharge of groundwater. The methodology adopted is exactly similar to what is represented in Eq. (1) except that the thematic maps and their weights used for this purpose are different; see Table 4 for details. Finally, the study area is classified on the basis of the computed overlay

index into categories such as ‘unsuitable’, ‘least suitable’, ‘moderately suitable’, ‘suitable’ and ‘most suitable’, with respect to its suitability for artificial recharge.

Estimation of runoff: SCS-CN method

For the construction of the runoff map, runoff values are estimated using the SCS-CN method. This SCS-CN method, developed by the soil conservation service of the US Department of Agriculture, involves the integration of soil group, land use classes and antecedent moisture conditions (Ramkrishnan et al. 2009; Kadam et al. 2012). Rainfall amount and runoff curve number are two major inputs in the SCS-CN method. The AMC (antecedent moisture condition), which represents the wetness of a particular area, is determined using the total rainfall of the last 5 days. According to Gupta and Panigrahy (2008), AMC is classified as AMC I (lowest runoff potential, rainfall <35 mm), AMC II (average condition, rainfall 35–52.5) and AMC III (highest runoff potential, rainfall >52.5 mm). Here, we used AMC class II. The curve number has a range from 0 to 100 and was obtained from USDA (1986). While a lower CN refers to low runoff potential, larger numbers indicate greater runoff potential. The values of CN used in this study are enlisted in Table 5. The curve number is related to soil moisture retention (S) and runoff (Q) by the following equations (Ramkrishnan et al. 2009; Kadam et al. 2012):

$$S = (1000/\text{CN}) - 10, \tag{2}$$

$$Q = (P - 0.2S)^2 / (P + 0.8S) \text{ for } P \geq 0.2S, \tag{3}$$

$$Q = 0 \text{ for } P < 0.2S, \tag{4}$$

where Q is the runoff in inches; P the rainfall in inches and S the soil moisture retention in inches.

In this study, the curve number is weighed with respect to the watershed area,

$$\text{CN}_w = \sum (\text{CN}_i \times A_i) / A, \tag{5}$$

where CN_w is the weighted curve number; CN_i the curve number from 1 to any number n; A_i the area with curve number CN_i and A the total area.

Table 3 Weights and ranks assigned to various thematic layers and their classes used for delineating groundwater potential zones (based on Mukherjee et al. 2012)

Layers	Class	Categories	Rank	Weightage
Geology (Geo)	Unconsolidated	Good	5	20
	Consolidated	Poor	1	
	Semi-consolidated	Moderate	3	
Geomorphology (Geom)	Pediment	Poor	1	10
	Alluvial plain	Moderate	3	
	Cuesta	Very poor	1	
	Denudational hill	Good	4	
	Inselberg	Good	4	
	Pediplain	Moderate	3	
	Water body	Very good	5	
Lineament density (Ld)	Very low	Very poor	1	15
	Low	Poor	2	
	Moderate	Moderate	3	
	High	Good	4	
	Very high	Very good	5	
Drainage density (D)	Very low	Very good	5	15
	Low	Good	4	
	Moderate	Moderate	3	
	High	Poor	2	
	Very high	Very poor	1	
Land use/land cover (LULC)	Barren area	Very poor	1	5
	Cultivated land, settlements/mining area	Moderate	3	
	Forest area	Very good	5	
	Urban area	Poor	2	
	Water body	Good	4	
Slope (Slo)	Nearly level	Good	4	10
	Very gentle slope	Moderate	3	
	Gentle slope	Poor	2	
	Moderate to steep slope	Very poor	1	
Soil (So)	A	Very good	5	10
	B	Good	4	
	C	Moderate	3	
	D	Poor	2	
Rainfall (R)	Very good	Very good	5	10
	Good	Good	4	
	Moderate	Moderate	3	
	Low	Poor	2	
	Very low	Very poor	1	
Digital elevation model (DEM)	Nearly level (79–238)	Very good	5	5
	Less moderate (238–319)	Good	4	
	Moderate (319–430)	Moderate	3	
	High (430–616)	Poor	2	
	Very high (616–975)	Very poor	1	

Table 4 Weights and ranks assigned to various thematic layers and their classes used for delineating artificial recharge sites (based on Saraf and Chowdhury 1998)

Layers	Class	Categories	Rank	Weightage
Geo	Unconsolidated	Most suitable	5	20
	Consolidated	Unsuitable	1	
	Semi-consolidated	Moderately suitable	3	
Geom	Pediment	Unsuitable	1	40
	Alluvial plain	Moderately suitable	3	
	Cuesta	Unsuitable	1	
	Denudational hill	Moderately suitable	3	
	Inselberg	Suitable	4	
	Pediplain	Moderately suitable	3	
	Water body	Most suitable	5	
LULC	Barren area	Unsuitable	1	10
	Cultivated land, settlement/mining area	Least suitable	2	
	Forest area	Least suitable	1	
	Urban area	Moderately suitable	3	
	Water body	Suitable	4	
Slo	Nearly level	Suitable	4	30
	Very gentle slope	Moderately suitable	3	
	Gentle slope	Least suitable	2	
	Moderate to steep slope	Unsuitable	1	

Table 5 Curve numbers used for the study area

Land use category	Soil group			
	A	B	C	D
Urban		88	91	93
Forest		55	70	77
Cultivated/settlement	98	98	98	98
Barren		79	86	89
Water body	100	100	100	100

Sensitivity analysis

Sensitivity analysis is the study of how the uncertainty in the output of a model or system can be apportioned to different sources of uncertainty in its inputs. (Babiker et al. 2005; Rahman 2008). Such analysis is often key to understanding the dominant process controls. While the use of multi-parameter indices facilitate reduced dependence on individual parameters, it is often criticised because of the data redundancy and subjectivity associated with the selection of weights and ratings. While sensitivity analysis has been primarily used to evaluate the accuracy of vulnerability indices such as DRASTIC (Saha and Alam 2014; Hasiniaina et al. 2010), it has been rarely used for water quality analysis (Machiwal et al. 2011). Sensitivity analysis is performed by the following two methods, which are (1) map removal sensitivity analysis (Lodwick et al. 1990) and (2) single-parameter sensitivity analysis (Napolitano and Fabbri 1996). The map removal sensitivity analysis was

performed by removing one or more parameters using the following equation (Babiker et al. 2005):

$$S = ((V/N - V'/n)/V) \times 100, \tag{6}$$

where *S* is the measure of sensitivity (variation index); *V* and *V'* are unperturbed and perturbed potential values; and *N* and *n* are the number of data layers used to compute *V* and *V'*. While the original groundwater potential index is referred to as the unperturbed potential value, those estimated using a fewer number of variables are considered as perturbed values. The analysis is performed by removing one or more variables at a time. Higher (lower) values of sensitivity measure (*S*) indicate greater (lesser) sensitivity of the variable towards the final output. The values of variation index can be positive or negative, depending on the values of the potential index. Positive *S* value indicates that the removal of a parameter reduces the value of the perturbed potential index and hence contributes positively towards the value of the unperturbed index. Similarly, negative values of *S* indicate that exclusion of certain parameters increases the value of GWPI, whereas inclusion of that leads to a decrease in the value of GWPI (Gogu and Dassargues 2000; Hammouri et al. 2012).

The single-parameter sensitivity analysis is carried out to analyse the influence of each of the nine variables on the final output of groundwater potential index. In this procedure, the effective weight of each parameter is compared with the theoretical weight. This analysis confirms that the parameter with higher effective weight is more sensitive compared to those with lower effective weight. In this

study the effective weight of each parameter is calculated using the following equation (Babiker et al. 2005):

$$W = (P_w P_s) / V \times 100, \quad (7)$$

where W is the effective weight of each parameter, P_r and P_w are the rating value and weight of each parameter and V is the overall potential value.

Results and discussion

Factors related to groundwater potential and artificial recharge

The contribution of each of the factors used in the computation of groundwater potential (Table 3) and identification of suitable sites for artificial recharge of groundwater (Table 4) are discussed in detail.

Geology factor

The rock types of an area significantly affect its groundwater potentiality (Shaban et al. 2006). Knowledge of lithostratigraphy is crucial to understand the nature and distribution of the water-bearing capacity (Fetter 1994) of the study area. Spatial distribution of the different geological units of the study area is shown in Fig. 3a. For the present study, the geology map is adopted from the annual report of the Central Ground Water Board, Government of India (CGWB 2009). The majority of the area, about three-fourth of the entire study area, is underlain by granitic gneiss and other metamorphic rocks. The remaining part is occupied by sandstone, shale and coal. In the study area, the hard rocks are mainly fractured, so it has some groundwater potential. A thin strip of sedimentary rocks, seen almost along the course of River Damodar, could have a relatively higher groundwater potential. Based on different properties of rocks, the study area is classified into three categories: (1) consolidated formation, (2) semi-consolidated formation and (3) unconsolidated formation.

Lithologic characteristics also impart significant control on the recharge of groundwater. The geology theme has been assigned an influencing factor of 20 % for both objectives of the present study. Each data class of the geology theme is also ranked on a scale 1–5. Consolidated rock formations are generally massive and prohibit infiltration of rainfall into the subsurface, thereby maximizing the possibility of runoff generation. On the contrary, unconsolidated and semi-consolidated rock formations contribute significantly as far as groundwater potential and recharge are concerned. As a consequence, consolidated and unconsolidated rock formations have been designated with the lowest and highest ranks, respectively.

Geomorphology factor

Geomorphology reflects the various landforms and structural features that play a significant role in land resource mapping, watershed studies and terrain evaluation. Since many of these features are favourable for the occurrence of groundwater, the groundwater condition varies for different geomorphologic features and hence classified in terms of groundwater potentiality. In this study, the geomorphology map is prepared from Landsat (TM) image. Figure 3b shows the major geomorphologic units of the study area. The major geomorphologic features of the study area include pediment, alluvial plain, cuesta, denudational hill, inselberg and pediplains. A detailed description of the geomorphological units is also listed in Table 6. Regional slope of the area, which is towards east, controls the alignment of the tributaries of River Damodar. While the Gomia block on the western side of the district has the highest topography, Chas and Chandankiyari blocks on the east are dominantly low lying. The average elevation of the undulating pediplain ranges from 200 to 350 m above MSL (mean sea level).

To analyse the geomorphologic controls on the hydrogeology of the study area, groundwater levels obtained from dug and bore wells are analysed across each geomorphologic unit within the study area. This has been done since groundwater level is not only a good indicator of groundwater potential, but is also supportive of the recharge potential of the area. Table 7 lists the values of groundwater level, averaged over a period of 10 years, for pre- and post-monsoon periods for each of the geomorphologic units identified within the study area and obtained from the Central Ground Water Board, Government of India. Results reveal that the deepest pre-monsoon groundwater levels are observed in a cuesta (12.63 mbgl) and the shallowest in water bodies (5.74 mbgl). Accordingly, the largest fluctuations between pre- and post-monsoon water levels are noted in pediments (7.10 mbgl) and the least in water bodies (2.95 mbgl). Depending on the pre- and post-monsoon water level fluctuation, each geomorphologic feature has been assigned a rank between 1 and 5. The geomorphology theme has been used for both objectives of the present study. This theme has been credited with a weight of 10 % for groundwater potential mapping and 40 % for identification of suitable artificial recharge sites.

Slope factor

Slope is the change in elevation of a surface and is expressed as a percentage or in degrees (Elewa and Quddah 2011). The slope of an area plays a significant role in the partitioning of rainfall into infiltration and runoff. While

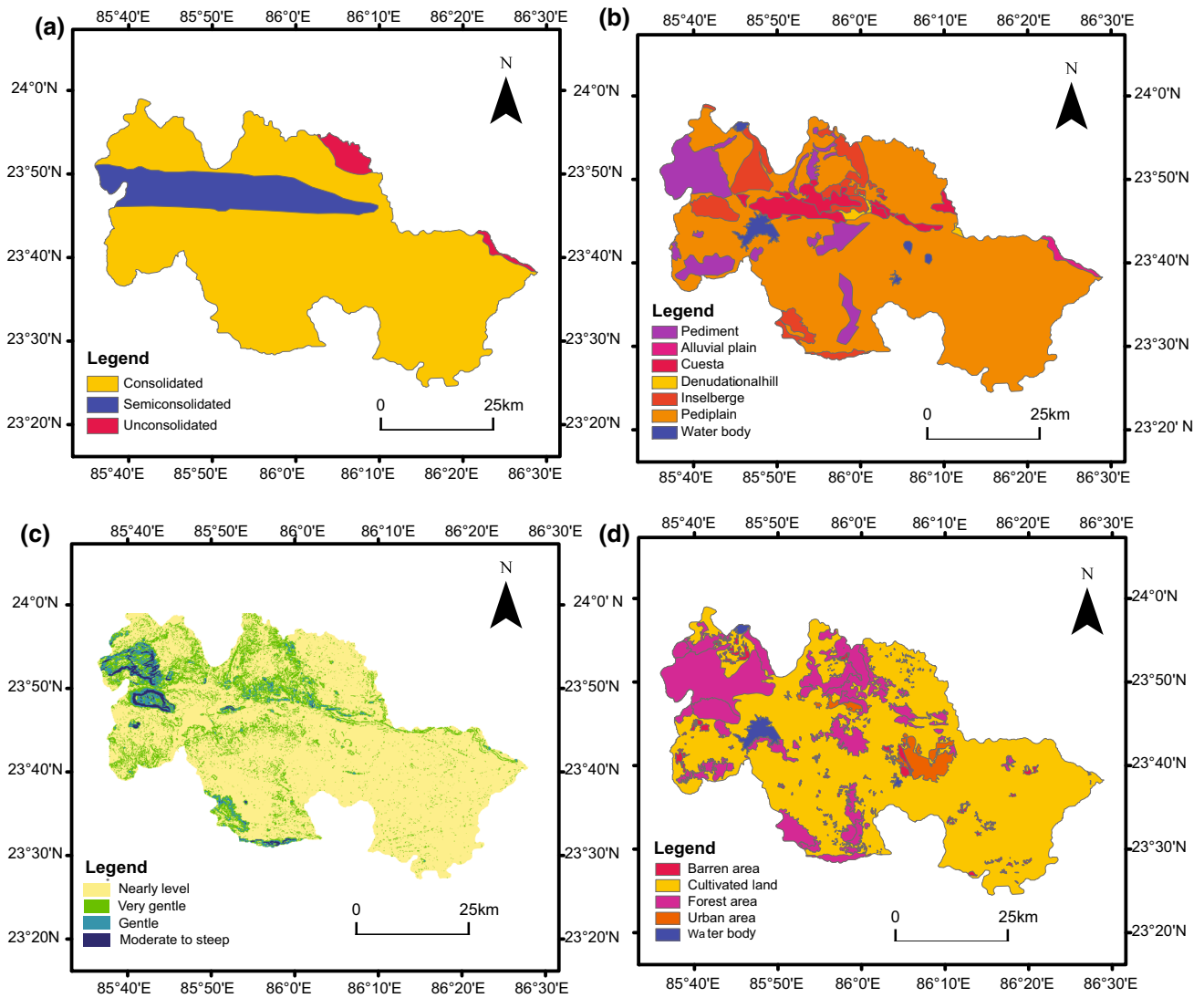


Fig. 3 Thematic maps of Bokaro District depicting the **a** geology, **b** geomorphology, **c** slope and **d** land use/land cover

Table 6 Geomorphologic units in the study area

Geomorphologic units	Description about units	Groundwater condition
Cuesta	A hill or ridge with a gentle slope on one side and a steep slope on the other side is known as cuesta	Poor
Pediment	It is a plain of eroded bedrock developed in between mountain and basin areas	Poor
Pediplain	Due to continuous erosion, pediments converge to form pedi plains	Moderate to good
Inselberg	These are isolated mounds rising above the general parts of a pediment	Moderate
Alluvial plain	These are composed of alluvial deposits of sand, silt and clay. Alluvial plains are found on the eastern side of the study area near the Damodar River course	Moderate to good
Denudational hill	Due to active process of weathering, mass wasting and erosion, denudational hills are found. These are found in the central part of the study area	Moderate
Water body	These are surface water bodies in the district	Good

Table 7 Groundwater levels across various geomorphologic features identified in the study area

Geomorphic features	Pre-monsoon water level (mbgl)	Post-monsoon water level (mbgl)	Water level fluctuation (mbgl)
Pediment	10.41	3.31	7.10
Pediplain	8.95	3.60	5.35
Cuesta	12.63	5.77	6.86
Denudational hill	9.65	4.75	4.90
Inselberg	9.45	4.88	4.57
Alluvial plain	7.6	2.41	5.19
Water body	5.74	2.79	2.95

the slope is directly proportional to the amount of runoff, it is inversely proportional to infiltration of surface water to groundwater storage (Rao and Jugran 2003). Steeper slopes lead to rapid movement of water during periods of rainfall and thus limits the likelihood of surface water infiltrating into the subsurface. The slope map of the study area, presented in Fig. 3c, is produced using the SRTM DEM. On the basis of slope, the study area is divided into four classes, which are ‘nearly level (0–2 %)', ‘very gentle slope (2–5 %)', ‘gentle slope (5–9 %)' and ‘moderate to steep slope (>9 %)'. Only the northwestern portion of the study area falls under ‘moderate to steep slope' class, while the rest, which comprises a major part of the study area, falls under the ‘nearly level' category.

The slope is also a common factor for groundwater potential mapping and identification of artificial recharge sites. The weightage stipulated for this theme is 10 % for groundwater potential mapping and 30 % for identification of artificial recharge sites. Since areas with slope enhance the potential for accumulation of rainfall and thereby recharge of groundwater, it has been given the highest rank. However, steeper slopes generate greater runoff and reduces the scope for surface water infiltration. For this reason, areas with steep slope are given the lowest rank for both the purposes.

Land use/land cover factor

This factor includes the distribution of residential areas and vegetation cover (Shaban et al. 2006). In the present study, land use/land cover map (Fig. 3d) is prepared on a 1:250,000 scale from Landsat-7 TM image using image interpretation elements such as tone, texture, drainage, structural fabric and relief found in the image and by comparing it with the topographic map of the area. In this process, land use/land cover of the study area is classified into five broad categories (e.g. barren area, forest area, urban area, cultivated land with some settlement and water body). For both the objectives land use/land cover is assigned the lowest percent of weight proportion compared to the other factors. While certain types of land use/land cover

can facilitate recharge of groundwater by reducing surface runoff, it may also have the potential to deplete groundwater storage through root water uptake and evapotranspiration.

Lineament density factor

Lineaments have considerable importance for groundwater potential mapping, since they act as primary controls of the movement and occurrence of groundwater in hard rock terrains (Sreedevi et al. 2005). Joints and fractures in a rock increase its secondary porosity and permeability to enhance the water-holding capacity and also enable efficient recharge of aquifers. Following the procedure of Moore and Waltz (1986), lineaments in the study area (Fig. 4a) are extracted utilizing false colour composite (FCC) of the Landsat 7 TM image. The lineaments shown in the map (Fig. 4a) are all natural, linear or curvilinear, features which are observed in the satellite image regardless of their origin. To avoid erroneous representations of non-geological linear features, the lineament map is cross-checked with the topographic map of the area. Since the concentration of the lineaments, i.e. the number of lineaments per unit area, is more pertinent towards the hydrogeologic properties of the subsurface material, the lineament density map (Fig. 4a) is prepared from the lineament map. For this purpose, a systematic method adopted by Sener et al. (2005) is implemented. In this map higher density indicates high potentiality and lower density indicates poor potentiality for groundwater. Accordingly, lineament density is divided into five classes, with values ranging from “very low” (0–5.24 km/km²) to “very high” density (40.58–77.37 km/km²) and assigned ranks of 1–5, respectively.

Drainage density factor

The drainage pattern of the study area shows a dominantly dendritic drainage system. The Damodar River flows from west to east almost through the middle of the study area. Konar and Jamunia are the two major tributaries of the

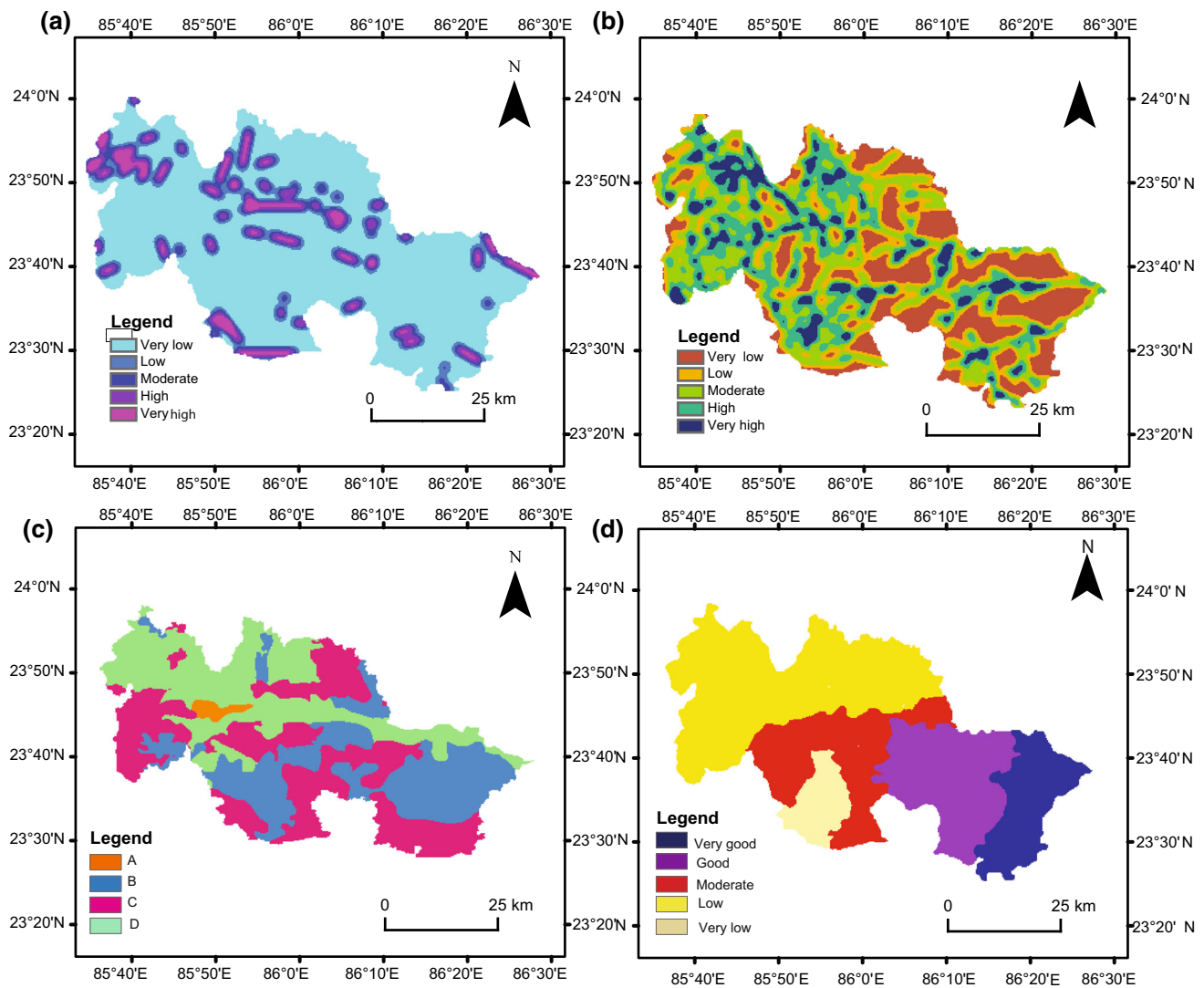


Fig. 4 Thematic maps of Bokaro District depicting **a** lineament density, **b** drainage density, **c** soil and **d** rainfall

Damodar River. Minor tributaries of the Damodar River present within the study area are Isri, Gobai, Kadwa and Khanj. The drainage system of the study area is primarily confined to weak zones such as joints, fractures and faults. For the present study, the drainage map is prepared from Landsat TM image and topographic map at the 1:250,000 scale.

Drainage density, which is defined as the unit length of stream per unit area, is a manifestation of the nature of the surface material and hence a primary control on groundwater recharges (Edet et al. 1998). Accordingly, impermeable surfaces would have higher surface runoff, since infiltration rate will be low, and thus greater drainage density (Yeh et al. 2009). The drainage density map (Fig. 4b) of the study area is prepared from the drainage map and classified into five different zones varying from low to very high density. Here, drainage density is assigned

the second highest weightage of 15 % alongside lineament density.

Hydrogeological soil group factor

According to the information from the National Bureau of Soil Survey and Land Use Planning, the soil map of the study area (Fig. 4c) is digitized and reclassified into four groups (A, B, C and D). Three soil orders, namely Entisols, Inceptisols And Alfisols, are observed in Bokaro District. Alfisols is the dominant soil order, which occupies around 62 % of the total area, followed by Inceptisols and Entisols, occupying about 21.4 and 12.7 % of the study area, respectively. These soil orders are reclassified into four groups based on its infiltration capacity and texture. Soil group A is characterized by high infiltration rate and hence low runoff potential, so it has been given the highest rank,

whereas group D soils have low infiltration rate and thus high runoff potential and given the lowest rank. Thus group A soils have greater groundwater potential in comparison to group D soils. Similarly, other soil groups B and C have been ranked according to their contribution and capacity to hold water. The soil type theme has been assigned an influencing factor of 10 % for the computation of groundwater potential.

Rainfall factor

Rainfall has the greatest contribution to natural groundwater recharge (Mukherjee et al. 2012) and a key factor in assessing the groundwater potential of an area. A higher rate of rainfall increases the water availability for the process of infiltration. For this study, a rainfall map (Fig. 4d) is prepared from station data, averaged annually over a period of 10 years (2003–2012) using the IDW technique. The rainfall map is classified into five groups from very good to very low. The map reveals that the Chandankiyari block in the eastern side of the study area records the highest amount of rainfall (1933 mm), while the Kasmar block on the southwestern side experiences the lowest amount of rainfall (899.56 mm). This thematic layer is also ranked on a scale 1–5 and has been given a weight of 10 % for groundwater potential mapping. Since the amount of rainfall directly influences the amount of water available for infiltration into the subsurface, the lowest and highest rainfall amounts are assigned the lowest and highest ranks, respectively.

Digital elevation model (DEM) factor

The altitude of the area above the mean sea level also has a vital role in groundwater recharge. While terrains with low altitude and gentle topography enhance the potential of surface water to infiltrate into the ground, thereby contributing towards the enhancement of groundwater potential, high-altitude topography augments the runoff potential thereby reducing the rate of rain water infiltration (Solmon and Quiel 2006; Rao 2006). For the current study, the digital elevation map is prepared from SRTM (CGIAR-CSI) (<http://srtm.csi.cgiar.org>) data. The DEM (Fig. 5a) illustrates the spatial distribution of elevation within the study area classified into five categories, namely ‘nearly level’ (79–238 m) ‘less moderate’ (238–319 m), ‘moderate’ (319–430 m), ‘high’ (430–616 m) and ‘very high’ (>616 m) and ranked from 1 to 5 according to the height above mean sea level. The eastern side of the study area has the lowest elevation (79–238 m above MSL) values, while the northwestern side has the highest. In the present study, the DEM theme has been given an influencing

weight of 5 % for the construction of groundwater potentiality map.

Groundwater levels

To validate the authenticity of the groundwater potential zones delineated above, following Eq. (1), observations of groundwater level from dug and bore wells in the study were investigated. For this purpose, observations of water level obtained from groundwater wells in the study area, spanning a period of 2002 to 2011, are utilized to produce a 10-year average of pre-monsoon and post-monsoon water level map using the IDW technique (Hutti and Nijagunappa 2011). This water level data was collected from the Central Ground Water Board (G. Roy 2013, personal communication). Average depth to groundwater levels for the pre- and post-monsoon periods are shown in Fig. 5b, c respectively. The eastern side and some central portion of the study area have the shallowest groundwater level (6 mbgl in pre-monsoon and 3 mbgl in post-monsoon). However, major parts of the study area have groundwater levels greater than 9 mbgl (pre-monsoon) and 5–6 mbgl (post-monsoon).

Runoff estimates

Runoff potential is often considered as a vital indicator of groundwater recharge potential of an area. Thus, it is essential for proper planning and execution of any artificial recharge initiatives. Based on the runoff generated using the SCS-CN method, the study area is classified into five classes from very low to high. The spatial distributions of these classes are illustrated in Fig. 5d. It is evident from Fig. 5d that ~7 % of the study area has high runoff (30–52 inches/year), 21 % moderate runoff (27–30 inches/year), 61 % low runoff potential (15–27 inches/year) and ~11 % very low runoff (8–15 inches/year).

Groundwater potential of the study area

The groundwater potential map of the study area is prepared, utilizing various layers of hydrogeologic and geomorphologic information, on the basis of the weighted index overlay method discussed earlier. The groundwater potential map of the study area (Fig. 6a) reveals three distinct categories representing ‘good’, ‘moderate’ and ‘poor’ groundwater potential. These zones demarcate areas where the subsurface has varying degrees of potential to store water and also indicates the availability of groundwater. The percent area distribution of each of the above-mentioned categories of groundwater potential are 5, 68 and 27 %, respectively.

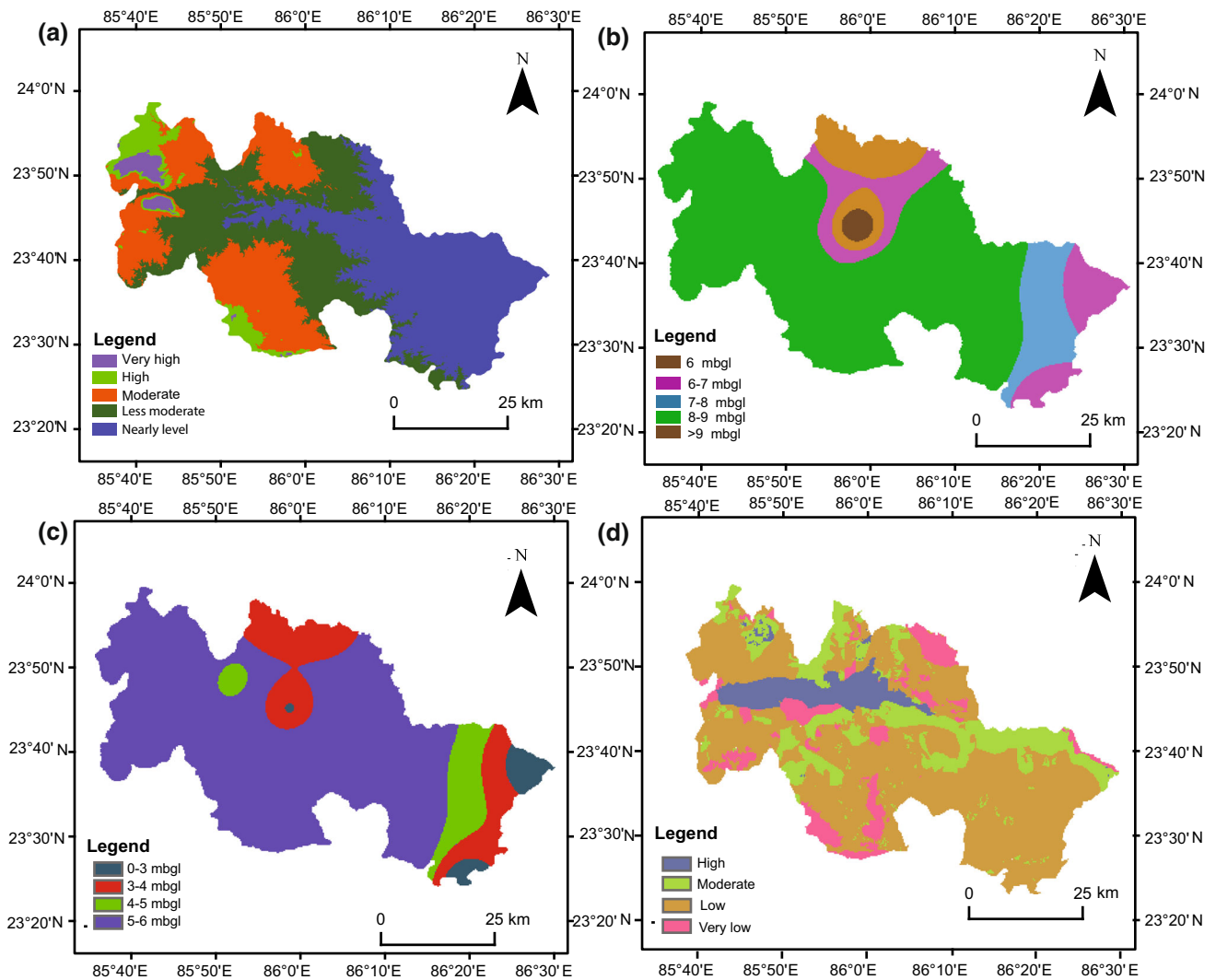


Fig. 5 Thematic maps of Bokaro District depicting **a** DEM, **b** pre-monsoon groundwater level, **c** post-monsoon groundwater level and **d** runoff

Results show that most of the areas have moderate groundwater potential. On the contrary, some portion of the Chandankiyari block and parts of the northern sides of Bokaro District are observed to have good groundwater potential. Higher potentialities of these areas are driven by a dominantly flat terrain and the presence of lineaments. Both these factors effectively enhance the rate of surface water infiltration compared to other parts of the study area. Even though major parts of the study area are underlain by rocks, which are almost impermeable, secondary porosity and permeability induced by lineaments and fractures render some parts of the study area to have moderate to good groundwater potential. Major portions of northwestern side and parts of the central Bokaro District have poor groundwater potential due to unfavourable geology and high slope. These factors are primarily responsible for producing high surface runoff and low groundwater

recharge. In addition, overexploitation in some of the areas, including those underlain by sedimentary rocks within the district effectuates poor groundwater potential in spite of its greater water-holding capacity.

Since rainfall is the key input for groundwater storage variations, depth to water level varies considerably between the pre-monsoon and post-monsoon periods. It has been observed that in areas with good potential, groundwater levels on an average vary between 6 mbgl (pre-monsoon) and 3 mbgl (post-monsoon), whereas in those with poor potential, groundwater level ranges from 9 mbgl (pre-monsoon) to 5 mbgl (post-monsoon). This is intuitive since areas with good groundwater potential have the capacity to retain the availability of groundwater and therefore maintain lower magnitudes of groundwater level fluctuation. These results establish the accuracy of the groundwater potential delineated in this study.

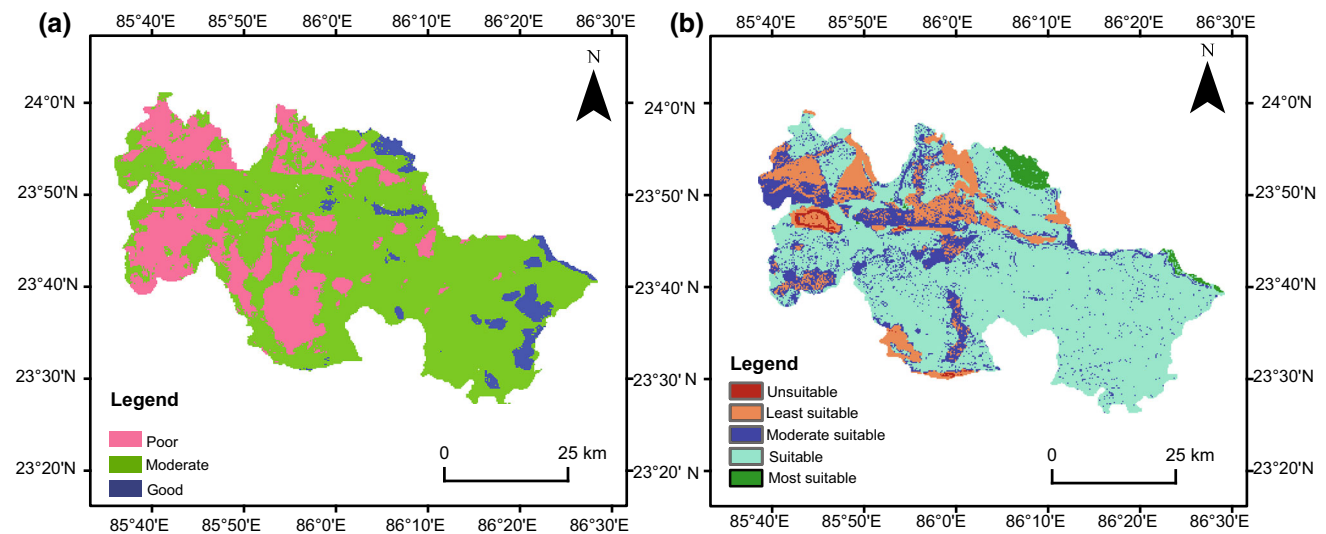


Fig. 6 Map showing the spatial distribution of **a** groundwater potential and **b** suitable sites for artificial recharge in the study area

Quantitative assessment of groundwater potential

A quantitative assessment of the exploitable dynamic groundwater reserve of the study area is estimated by the following equation (Hutti and Nijagunappa 2011; Chowdhury et al. 2009):

$$R_e = \Delta h \times A \times S, \quad (8)$$

where R_e is the average annual dynamic exploitable/utilizable groundwater reserve; Δh the 10 years average groundwater fluctuation between pre-monsoon and post-monsoon periods; A the area of the groundwater potential zone; and S the storage coefficient of the aquifer. For this purpose, data on existing wells are overlaid on the groundwater potential map and R_e is estimated for each of the different groundwater potential zones. Results show that the average annually exploitable groundwater reserve is 87.18 million cubic metre (MCM) for areas with good groundwater potential. R_e estimates for moderate and poor zones are 962.11 MCM and 53.312 MCM, respectively. Thus, the total amount of average annually exploitable groundwater reserve is conspicuously lower for the poor zones, compared to the other zones, despite its significantly larger spatial extent. The moderate zone has conspicuously greater exploitable groundwater reserve amongst others, which is inferable from the significantly larger spatial coverage. Note that this exploitable reserve of groundwater can be considered as sustainable yield for the respective zones, since these are the volumes of groundwater replenished annually. However, this is a first-order approximation; detailed field pumping tests should be done to determine sustainable yields at individual well sites.

Results of the sensitivity analysis

In spite of the proven effectiveness of multi-parameter indices, the contribution of the individual parameters used in these indices is often highly debated. The sensitivity analysis of the computed groundwater potential index is analysed here both in terms of the number of significant parameters and their effective weight.

Map removal sensitivity analysis

Map removal sensitivity analysis is implemented in two stages. In the first stage, the sensitivity of GWPI as a result of removing one parameter at a time is analysed. This analysis defines that higher (lower) values of mean variation index (S) indicate greater (lesser) degree of sensitivity towards the removed parameter. Table 8 presents the statistics of variations in the potential index (S) as a result of removing only one parameter at a time. Results reveal that the GWPI is most sensitive to the slope and drainage density parameters (mean variation index = 17.3 %). Although to a lesser degree, computation of GWPI shows significant sensitivity towards the removal of the geology (15.83 %) layer. This, however, is probably because of the relatively higher theoretical weight assigned to the geology layer.

In the second stage, more than one parameter is removed for the quantification of their sensitivity towards the computation of GWPI. Table 9 shows the values of the sensitivity measure obtained due to the removal of one or more parameters at a time. According to this analysis, the least average variation index resulted after removing the geology layer (15.83 %). As more data layers are excluded,

Table 8 Statistic of map removal sensitivity analysis

Parameters removed	Variation index (%)			
	Min	Max	Mean	SD
Slo	2.99	27.78	17.33	3.09
D	−2.17	32.08	17.3	6.07
Geo	−6.89	43.46	15.83	5.53
So	4.76	30.3	14.04	4.09
Geom	2.47	23.26	10.32	3.26
R	2.6	22.73	9.85	3.72
Ld	−5.77	34.69	8.31	5.43
DEM	1.41	13.89	7.19	1.83
LULC	1.28	15.15	6.21	2.06

SD standard deviation

the value of the average variation index increases sequentially, thereby highlighting the significance of each data layer in the quantification of groundwater potential of the area. However, most importantly, certain variables are found to be more sensitive than the others as evident from the non-linear increase in the values of average variation index with respect to the number of parameters used. For example, removal of drainage density and slope parameter resulted in the largest change (17.3 %) in the value of the variation index, while the removal of the geomorphology layer produced a change of only 3.9 %. Significantly large values of average variation index also confirm the importance of each thematic layer and are therefore crucial for determining the groundwater potential of the area.

Single-parameter sensitivity analysis

While the importance of parameters is quantified by map removal sensitivity analysis, the significance of the weights assigned to each layer is assessed by single-parameter sensitivity analysis. This analysis compares the theoretical weight, i.e. the weight assigned, of a layer with its real weight. Results demonstrate the drainage density and slope

as the most effective parameters in the computation of GWPI, with an average effective weight of 17.3 % (Table 10), which is also in agreement with the results from map removal sensitivity analysis. Table 10 reveals the obvious differences in the effective and theoretical weight of individual layers. While these differences are most prominent for geology, lineament density and soil parameters, the effective and theoretical weights are almost similar in the case of geomorphology, rainfall and LULC. It is also important to note that geology has an effective weight that is significantly lower than the assigned weight. Results discussed here emphasize the importance of obtaining precise and detailed data on certain parameters, such as slope, drainage density and geology, for accurate estimation of GWPI.

Suitable sites for artificial recharge in the study area

Artificial recharge is often the most viable approach to revive depleting groundwater resources. However, the effectiveness of any artificial recharge initiative is heavily dependent upon the identification of suitable recharge sites. In this study, identification of suitable artificial recharge sites is performed by weighted overlay technique utilizing key hydrogeologic parameters such as geology, geomorphology, land use/land cover and slope. In this method, each of these parameters are assigned weights in accordance with their contribution towards suitability for artificial recharge (Table 4). Finally, these thematic layers are integrated and a composite map is produced to illustrate the varying suitability of the study area for artificial recharge (Fig. 6b). The resulting map of the study area has been classified into five classes, such as ‘unsuitable’, ‘least suitable’, ‘moderately suitable’, suitable and ‘most suitable’ artificial recharge sites. Spatially, each of these classes cover 0.53, 12.5, 15.45, 69.5 and 2.02 % of the study area, respectively. Due to the presence of deep forest cover and high slope, the northwestern side of the study area is identified to be ‘unsuitable’ to ‘least suitable’ for

Table 9 Statistics of map removal sensitivity analysis using multiple parameters at a time

Parameters used	Variation index (%)			
	Min	Max	Mean	SD
Geom, Ld, D, LULC, Slo, So, R, DEM	−6.89	43.46	15.83	5.53
Ld, D, LULC, Slo, So, R, DEM	−9.52	47.92	19.75	5.87
D, LULC, Slo, So, R, DEM	2.7	59.32	28.04	7.07
LULC, Slo, So, R, DEM	11.11	71.43	45.35	6.71
Slo, So, R, DEM	19.44	80	51.57	6.79
So, R, DEM	47.22	85.71	68.89	5.49
R, DEM	65.91	92.96	82.96	4.12
DEM	86.11	98.11	92.81	1.83

SD standard deviation

Table 10 Statistics of single-parameter sensitivity analysis

Parameters	Theoretical weight (%)	Effective weight (%)			
		Min	Max	Mean	SD
Slo	10	2.99	27.78	17.31	3.09
D	15	4.17	31.91	17.3	6.05
So	10	4.76	30.3	14.04	4.09
Geom	10	2.44	23.26	10.33	3.26
R	10	2.6	22.73	9.85	3.72
Geo	20	5.33	30.3	9.46	4.94
Ld	15	3.75	32.61	8.31	5.23
DEM	5	1.41	13.89	7.19	1.83
LULC	5	1.28	15.15	6.21	2.06

SD standard deviation

artificial recharge. Overall, only two small regions of the study area, with favourable hydrogeological conditions for groundwater recharge, are identified as the most suitable sites for artificial recharge. These sites are located within the Nawadih block and along the northern edges of the Chandankiyari block.

The artificial recharge sites in the study area, as identified by remote sensing and GIS techniques, are validated by computing runoff estimates for the study area. Areas with high groundwater recharge potential allow rapid infiltration of surface water generated from rainfall events to efficiently recharge the aquifer in the area. Accordingly, these areas are characterized by low runoff potential. On the contrary, areas with low recharge capabilities inhibit infiltration of surface water, thereby generating a greater amount of surface runoff. Hence, surface runoff is often used to make a first-order assessment of the recharge potential of an area (Anbazhagan et al. 2005). Analysis of the spatial disposition of areas classified on the basis of runoff estimates (Fig. 5d) and that on the basis of suitability for artificial recharge (Fig. 6b) demonstrate that, except for a few regions, sites most suitable for artificial recharge co-occur with those having the lowest runoff, while regions that are 'least suitable' coincide with those having the highest runoff generated.

Summary and conclusion

The groundwater resource of Bokaro District is mostly constrained by limited availability, indiscriminate exploitation for agricultural and domestic purposes and drainage from mining-related activities. Hence, control and regularization are crucial for proper utilization of this vital resource, which in turn underscores the importance of assessing the groundwater potential of the area. This study integrates

physiographic and geologic factors that govern the movement and occurrence of groundwater to provide spatially distributed information on groundwater potential and suitability for artificial recharge to augment the limited groundwater reserves of the study area. Results indicate that certain portions of the alluvial plains, especially in the northern and eastern part of the district, possess good groundwater prospects. This region, which is about 5 % of the study area, is underlain by lithology with high porosity and permeability. The presence of lineaments leads to the development of moderate groundwater potential which covers about 68 % of the study area. Localized lineaments allow surface water to infiltrate through weak zones; otherwise, around 27 % of the study area has poor groundwater potential zone. The slope of an area controls the amount of surface runoff; in case of very gentle slope, surface runoff is less so the chances of infiltration are more. Hence, the combination of low upland area and the occurrence of high lineament density yield a very good groundwater potential for the Chandankiyari block in the eastern side of the district. The average annually exploitable groundwater reserve for areas with 'good', 'moderate' and 'poor' groundwater potential is estimated to be 87.18 MCM, 962.112 MCM and 53.312 MCM, respectively. Sensitivity analysis, performed to evaluate the influence of parameters on groundwater potential mapping, demonstrates significant contributions from each of the parameters used. Results reveal slope and drainage density to be most sensitive towards the computation of groundwater potential index alongside geology and soil characteristics.

Due to overexploitation of groundwater, different parts of the study area face critical water scarcity problems. Therefore, implementation of suitable artificial recharge techniques is necessary to augment the attenuating groundwater resource of the study area. The suitability of the study area for the execution of such techniques is also assessed in this study. In this regard, the study area is categorized as 'unsuitable', 'least suitable', 'moderately suitable', 'suitable' and 'most suitable' sites. Due to thick forest cover and high slope, the northwestern side of the study area is mostly identified as 'unsuitable' and comprises ~0.53 % of the total area of Bokaro District. Major parts of the study area, ~69.5 %, are considered to be suitable for artificial recharge. The moderately suitable sites, occupying nearly about 15.45 % of the study area, are mostly characterized by high lineament density with a greater capacity to hold groundwater. The least suitable sites, occupying nearly about 12.5 % of the study area, are mostly with steep slope and thick forest cover. Overall, only two regions are found to be highly suitable for artificial recharge, which comprises only 2.02 % of the total area of the district. Areas with high to moderate suitability for artificial recharge are recommended to be used as

primary sites for undertaking artificial recharge projects in the study area. Suitability for artificial recharge is further corroborated with runoff estimates computed using the SCS-CN model. Results reveal that areas with high recharge potential also correspond well with low runoff estimates and vice versa. The efficacy of the results presented here could be further improved by the utilization of more rigorous in situ sampling of field data and consideration of other methods involving more thematic information directly or indirectly related to the movement and occurrence of groundwater. The final results portray favourable prospective zones for groundwater in the study area and can have major implications for better planning and management of groundwater resources of the Bokaro District.

Acknowledgments We thank the Central Groundwater Board, Ranchi, Jharkhand, for providing us with valuable well data and helpful guidance. We are also grateful to the anonymous reviewers for their vital suggestions in improving the quality of the work presented here.

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