



Delineation of groundwater potential zones of Atrai–Sib river basin in north-west Bangladesh using remote sensing and GIS techniques

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Abstract

Present research work is carried out in the Atrai–Sib river basin in the drought-prone but agro-based Barind area in the north-west of Bangladesh to delineate the groundwater potential zones using integrated approach of remote sensing (RS) and geographic information system (GIS)-based multi-criteria evaluation. Decreasing trend in rainfall along with increasing population in this drought-prone area calls for a sustainable development of the groundwater resource. The river basin possesses dendritic drainage pattern and major portion of runoff water allows more infiltration to recharge the groundwater and is, therefore, a potential for groundwater occurrence. The gentle to flat river basin is of ‘excellent’ category for groundwater management because of favorable infiltration to maximum time of runoff percolation. Here, seven different thematic layers such as, geomorphology, drainage density, rainfall, lithology, lineament density, slope and land use/ land cover (LULC) are integrated in GIS environment to study groundwater potentiality. Corresponding normalized rates for the classes in a layer and weights for the thematic layers are computed using Saaty’s Analytical Hierarchy Process (AHP), and then aggregated thematic map is prepared using a weighted linear combination (WLC) method. Map-removal and single-parameter sensitivity analysis are used to examine the effects of removing any thematic layer on the groundwater potential zones and to compute effective weight, respectively. About 226 km² (6% of the study area) is designated as very good groundwater potential zone, whereas that of good, moderate, very poor and poor groundwater potential zones cover 407 km² (11%), 720 km² (19%), 997 km² (26%) and 1418 km² (38%), respectively. Sensitivity analysis shows that the groundwater potential zonation in the study area is most sensitive to lineament density (mean variation index 2.66), which is the most effective thematic layer in the groundwater potentiality zone (mean effective weight of 27.13%) and supports the need for future river basin development and management. This study can help to identify the groundwater potential zones of this drought-prone area that will lead towards the planning of the integrated water resources management.

Keywords Groundwater potentiality · Remote sensing · GIS · Atrai–Sib river basin · Bangladesh

Introduction

Water is one of the most valuable natural resources which support human life and their socio-economic development. Not only its sufficient quantity, but acceptable quality is most important to sustain human activities such as domestic needs, agriculture, and industries in both urban and rural areas (Todd and Mays 2005). It helps in poverty alleviation and reduction to achieve MDG target for developing countries such as Bangladesh. Here, significant growth in

irrigated agriculture has happened in the past decade which resulted in increased demand for groundwater. But, the mismanagement of the groundwater resource to supply ever increasing demand finally leads to water shortage and pollution (De Villiers 2000; Tsakiris 2004). The unsustainable groundwater use is increasing apparently and the key concern, particularly the drought-prone but agro-based Barind area in the north-western part of Bangladesh.

Various scientific research already reported hydrogeological and hydrological factors as controlling groundwater potentiality indicators such as geomorphology, drainage pattern, soil cover, rainfall, geology, slope, and land use/land cover (LULC). In a different way, they affect groundwater potentiality of an area with spatio-temporal consideration (Sener et al. 2005; Sreedhar et al. 2009; Avtar et al. 2010;

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Gaur et al. 2011; Adiat et al. 2012; Fennta et al. 2015). Recent scientific studies embrace digital satellite data that provide baseline information about geomorphology, geology, lineaments, LULC and other factors that control the occurrence of groundwater and its potentiality. In this context, geospatial tools such as remote sensing (RS) and geographical information system (GIS) have emerged as effective tools for analysis of voluminous geomorphic, geologic and hydrological data and for the simulation modeling of complex features in decision-making level (Goodchild 1993; Lu et al. 1997; Gogu et al. 2001; Gossel et al. 2004; Stafford et al. 2008). Recent studies reveal that the integrated RS and GIS technique application helps for groundwater exploration in pinpointing the target areas for conducting detailed hydrogeological and geophysical surveys in the ground surface.

Despite the enormous importance of groundwater resources in the development process, only very limited regional hydrogeological and river basin hydrological studies have been carried out in the past few decades. Bangladesh as a lower riparian country in the Ganges–Brahmaputra–Meghna (GBM) deltaic region in South Asia ranks second in the socio-economic context in the list of most vulnerable countries in the world. Here, previous achievements and future efforts to reduce poverty are threatened, particularly by reduced availability of fresh water resource and food security where lives and livelihoods depend on water and agriculture. Like other natural calamities and disasters such as flood or cyclone (Brammer 1996; Alexander 1995), drought affects especially Barind area in the north-western part of the country more severely where monsoon is curtailed. This area is granary where agricultural practices run mostly by groundwater irrigation. A significant growth in irrigated agriculture in past decade has resulted in the increasing demand of groundwater, but there is a significant gap in the assessment of groundwater resources and identification of groundwater potential zones. Here, the recent declining trend of the groundwater table (GWT) is at higher rate than earlier. After 2002–2004, GWT did not return to its original level (Jahan et al. 2015). Moreover, the changing climatic scenario along with yearly irregular frequency and intensity of rainfall makes it difficult for planned management of water resource (Rahman et al. 2016). So, there is an urgent need for the evaluation of water resources in the area for the sustainability of livelihood and ecosystem.

But unfortunately till now no studies have been carried out on the groundwater potentiality in the Barind area especially its south-eastern part in Atrai–Sib river basin using RS and GIS techniques. But the sustainable development of the surface and groundwater resources must be considered as the viable alternative to support the community in this drought-prone water scarce area to protect the declining trend of groundwater resource mainly for livelihood by maximizing agricultural output. Hence, present research work attempts to

prepare groundwater potential zonation map applying geospatial technologies such as RS and GIS and multi-criteria analysis viz., geomorphology, geology, drainage pattern, soil cover, slope, LULC, etc. for better planning, utilization and management of this valuable resource. This study is important for sustainable use of the groundwater resource thereby enhancing groundwater recharge by proper management.

Study area

The study area, the Atrai–Sib river basin (Fig. 1), is characterized physiographically by two distinct landforms: the Barind Tract and the floodplains. According to Morgan and McIntire (1959), Barind Tract is one of the oldest Pleistocene terraces, north–south dome-shaped area (20–25 km wide in east–west direction) and covered by older deposits—Pleistocene sediments, popularly known as Barind clay encountered within the Bengal Basin. The Tract, with comparatively high elevation of 47.0 m above MSL in its central part is edged parallelly by river valleys of 11.0 m above MSL in the southeast in the floodplain area. Khandoker (1987) shows that the Barind Tract was elevated as horst block at the close of Pleistocene. It is south-westerly tilted block and its south-eastern margin is delineated by the Atrai–Sib river basins. The Atrai–Sib river basin has greater thickness of upper clay-silt layer with greater depth of the main aquifer than the Barind Tract. The river basin is characterized by steep faulting having downthrown blocks towards south with numerous streams, depressions and channels along the flow direction of the rivers (Jahan and Ahmed 1997). The surface deposits of the floodplain area are classified as stream and inter-stream deposits which are generally called as the Recent sediments and deposited mainly by the major rivers along with their numerous tributaries and distributaries. The physiographic map of the Barind area is shown in Fig. 2.

The Barind area enjoys mainly three seasons: winter (Nov–Feb)—cool and dry with almost no rainfall; pre-monsoon (Mar–May)—hot and dry; and monsoon (Jun–Oct)—rainy. The average annual rainfall for the period of 1980–2012 in the area is 1525 mm (much less than the national average of 2550 mm), whereas in the dry and monsoon seasons, average values stand at 244 and 1266 mm, respectively. Magnitude of change of annual rainfall shows a significantly decreasing trend (20–23 mm/year) along with negative periodic (dry and rainy) trends (Jahan et al. 2015). The monthly average temperature for the same period ranges from 10 °C (January) to 33 °C (May) with increasing rate of 0.0208 °C/year. The moderate-to-high meteorological drought-risk conditions prevail here that creeps towards semi-aridity in recent years (Jahan et al. 2008).

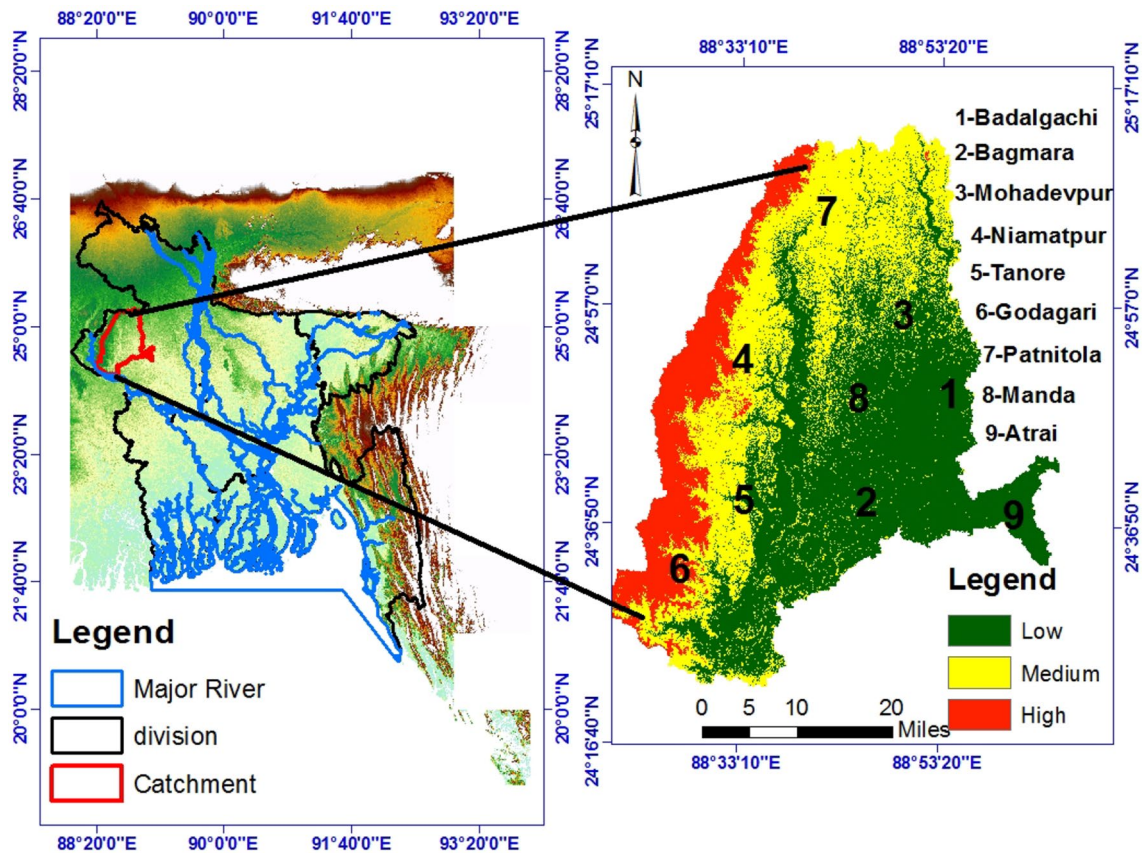


Fig. 1 Location map of the Atrai–Sib river basin

The area is characteristically recipient of less amount of rainfall, low infiltration capacity of soil which is insufficient for groundwater recharge, limited scope to conserve rainwater in rivers, canals, and swamps (*beels*); and existence of potential aquifer at greater depth for large scale groundwater development makes the area a water-scarce one. The accretion to groundwater from rain and floodwater during the monsoon results in the rise of groundwater level. After monsoon, part of the recharged groundwater is discharged into the rivers, streams and low-lying areas. The general outflow of groundwater from the Barind Tract is towards the major rivers, streams and low-lying areas at the end of rainy as well as during dry season (Jahan et al. 2010).

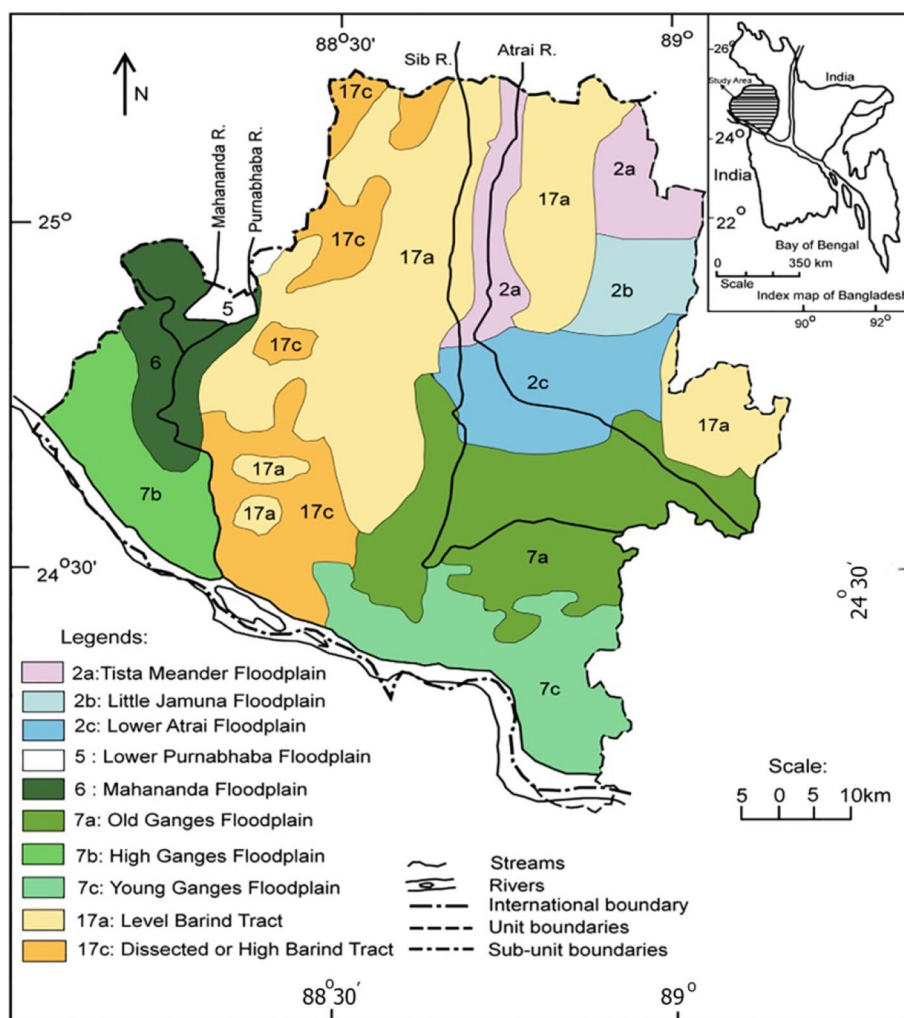
Methodology

The methodology designed for the present research work for delineation of groundwater potential zones using multi-parametric data set such as conventional maps from secondary source viz. topographic maps, rainfall data, geological map, etc., and RS information. Here RS information is used directly for the thematic map preparation. The themes of

information include geomorphology, lithology, soil type, slope, LULC, etc. The Atrai–Sib river basin area is delineated from the Shuttle Radar Topography Mission (SRTM), Digital Elevation Model (DEM) and topographic sheets of the Survey of Bangladesh (SoB) using data preparation option of ERDAS Imagine for making the areas of interest. The DEM received from SRTM (Mark 1984; Tarboton 1997) [US geological survey website (<http://www.earthexplorer.usgs.gov> update 2014 with 30 m resolution)] has been used in present study. Here, an integrated approach of multi-spectral satellite data, DEM and topographical sheets of the SOB are used for database preparation and parametric calculation of river basin such as geomorphic feature, LULC, vegetation cover, and soil type. To extract the required input variables, RS information and secondary data are processed using GIS software packages. Accordingly, Landsat 8 satellite (December 2014) image is used to produce and update the thematic information of the river basin using Spatial Analyst Tool of Arc GIS 10.2.

In present study, lithology as parent material of soil is considered instead of later as an important factor. Here, geomorphological data are extracted from USGS, and slope values are obtained from SRTM-DEM using spatial analyst

Fig. 2 Physiographic map of Barind area (Alam 1998; Brammer 1996)



tool. The drainage network map of the area is prepared from topographic map and the DEM. From the drainage network map, drainage density is calculated by spatial analyst tool. The rainfall data are obtained from ten rain-gauge stations (RGS) of the Bangladesh Water Development Board (BWDB) which exist in the area and rainfall map is prepared using inverse distance weight (IDW) interpolation from ten RGS providing point rainfall data. Here, all analysis are rectified and then geo-referenced using the Universal Transverse Mercator (UTM) coordinator system projection and the world geodetic system (WGS84) datum considering the Ground Control Points (GCPs).

To delineate groundwater potential zones of the Atrai–Sib river basin, each of the seven different thematic layers are integrated in GIS-based multi-criteria evaluation. The evaluation is based on Saaty's AHP (Saaty 1980) to compute rates for the classes in a layer and weights for the thematic layers, and the Weighted Linear Combination (WLC) method (to aggregate thematic layers) are the steps used to delineate groundwater potential zones. In this method, the relative importance of

individual class within the same map and thematic maps are compared to each other by pair-wise comparison matrices, where each criterion is compared with the other, relative to its importance, on Saaty's scale from 1 to 9 (scale 1 represents equal importance between two factors, and 9 shows the extreme importance of one factor compared to the other one). The scale of preference between two parameters in Saaty's AHP (Saaty 1980) is shown in Table 1 and Saaty's ratio index (RI) for different n values (in this case lithology, lineament density, geomorphology etc.) are given in Table 2 (Saaty 1980).

In the present study, sensitivity analysis for the influence of rates and weights assigned to each class and thematic layer on the output has been carried out. In the sensitivity analysis, study has performed through map-removal (Lodwick et al. 1990) and single-parameter (Napolitano and Fabbri 1996) techniques.

Table 1 Scale of preference between two parameters in AHP (Saaty 1980)

Scale	Degree of preference	Explanation
1	Equally	Two activities contribute equally to the objective
3	Moderately	Experience and judgment slightly-to-moderately favor one activity over another
5	Strongly	Experience and judgment strongly or essentially favor one activity over another
7	Very strongly	An activity is strongly favored over another and its dominance is showed in practice
9	Extremely	The evidence of favoring one activity over another is of the highest degree possible of an affirmation
2, 4, 6, 8	Intermediate values	Used to represent compromises between the preferences in weights 1, 3, 5, 7 and 9

Table 2 Saaty's ratio index (RI) for different values of n (Saaty 1980)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

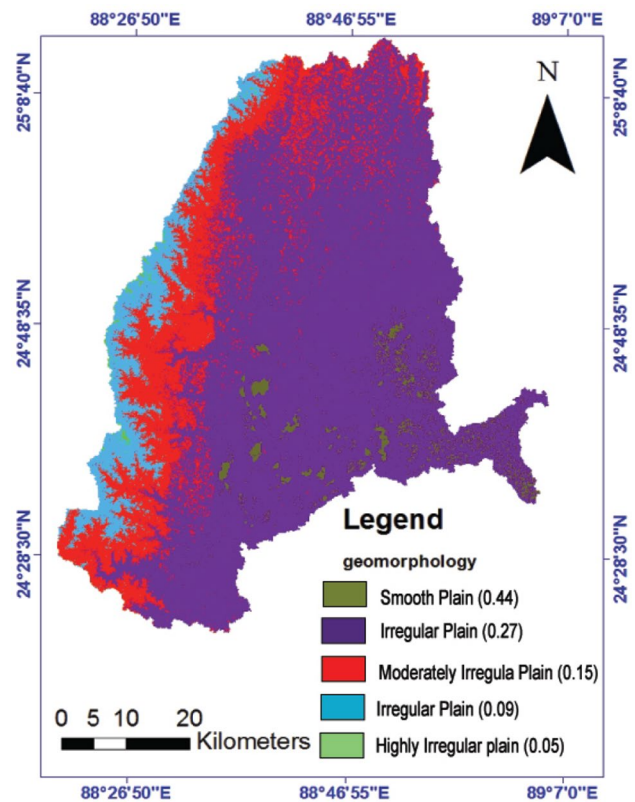
Results and discussions

Evaluation of physical factors controlling groundwater occurrence

Geomorphology

The geomorphology of an area plays an important role in the occurrence of groundwater (Jaiswal et al. 2003; Chowdhury et al. 2009; Machiwal et al. 2011; Fashae et al. 2014). Among seven different thematic layers, geomorphology is assigned highest weight, because it plays a dominant role in the movement and storage of groundwater in an area (Thomas et al. 2009). Geomorphological mapping provides the identification and characterization of various landforms along with structural features. The geomorphological units observed in the river basin area are ranked based on suitability for groundwater occurrence as smooth plain > irregular plain > moderately irregular plain > irregular plain and highly irregular plain. The geomorphological classes and their corresponding rates are given in Fig. 3 and Table 3. The smooth plain mostly covering the study area and followed by irregular plain has more impact in the occurrence of groundwater (Soumen 2014) and leads to the delineation of hydromorphological usefulness.

The geomorphological features such as topography and drainage of the study area highly affect the occurrence and flow direction of surface and sub-surface water during rainy season, the water percolation and flow from the Barind Tract to the river basin. Physiographically, the study area based on relief and seasonal flooding lies in the floodplain between the eastern and the central Barind Tract. The Barind Tract constitutes 54% of the total area and the rest 46% covers the floodplain of the Atrai, Sib, Tulshiganga

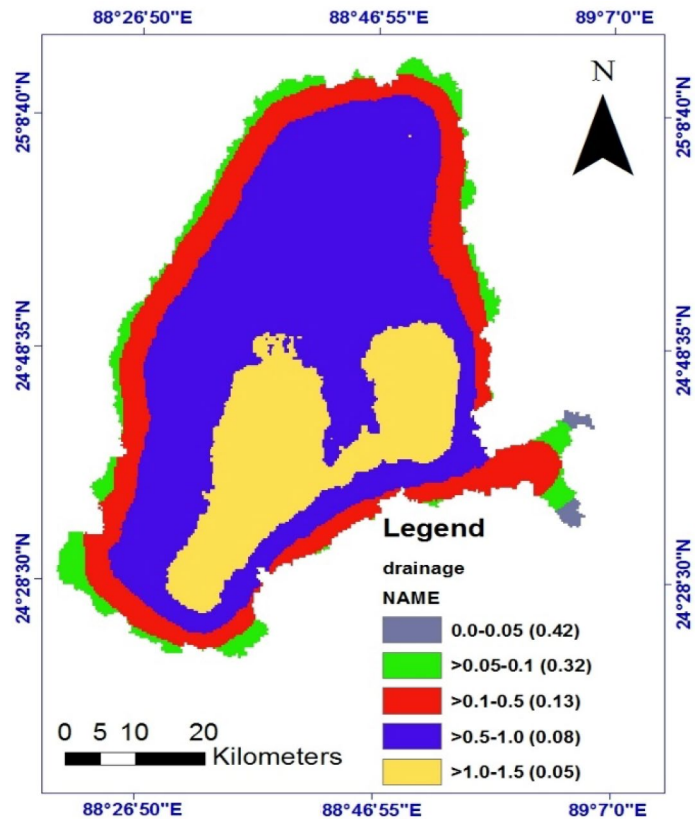
**Fig. 3** Geomorphology map of the study area

rivers, etc. in the eastern side, and the Mahananda and Purnabhaha rivers, etc. in the western side. The more elevated Barind Tract have well-developed drainage patterns between the Mahananda and the Atrai rivers which are the expression of the structural control on the drainage system. Hirst (1917) expressed that the Atrai, Sib, Purnabhaha, etc. rivers are antecedent streams and they show incised meandering courses. The shifting of the river courses are

Table 3 Pair-wise comparison matrix for geomorphological classes (CR=0.01)

	SPL	IPL	MI	I	HI	Rate
SPL	1	2	3	5	6	0.44
IPL		1	2	3	5	0.27
MI			1	2	3	0.15
I				1	2	0.09
HI					1	0.05

SPL smooth plain, *IPL* irregular plain, *MI* moderately Irregular, *I* Irregular, *HI* Highly Irregular

Fig. 4 Drainage density map of the study area

indicative of the neotectonic activities in the north-western part of Bangladesh (Gafoor 1982). The Barind Tract, a south-westerly tilted fault block, is flanked on the west by the Mahananda river floodplain while its eastern side is delineated by the Atrai, Sib rivers, etc. (Khandoker 1987). The general trend of outflow of groundwater is towards the major rivers, streams and low-lying area at the end of rainy as well as dry seasons. Comparison with the topographic configuration of the area shows that the trend of groundwater and surface water flow almost follows the surface gradient of the tract and the floodplain. The groundwater table is at shallower depth in the Atrai–Sib river basin than that in the Barind Tract, because the flowed water from the higher elevated land accumulates here and the area has good groundwater potentiality. At the same, the land forms of the area have a great role on the groundwater

occurrence and flow direction as the Barind Tract has dome shape and the Atrai–Sib river basin has almost flat land area.

Drainage density (Dd)

Drainage pattern of an area gives an idea about nature and characteristics of surface and subsurface formations. Drainage density of an area is an inverse function of permeability of lithological formations (Jaiswal et al. 2003). The drainage network map in the study area is generated from SRTM-DEM and further verified with topographic maps (scale 1:50,000). The drainage density values in the area vary from 0 to 1.5 km/km², whereas major portion of the area has Dd value of 0.5–1.5 km/km². So Dd is an important parameter in delineating the groundwater potential zones, which

Table 4 Pair-wise comparison matrix for drainage density (km/km²) classes (CR=0.03)

	0.0–0.05	>0.05–0.1	>0.1–0.5	>0.5–1.0	>1.0–1.5	Rate
0.0–0.05	1	2	3	5	7	0.42
>0.05–0.1		1	2	3	5	0.32
>0.1–0.5			1	2	3	0.13
>0.5–1.0				1	2	0.08
>1.0–1.5					1	0.05

are found to be rich mostly in areas with low drainage density (Jaiswal et al. 2003; Chowdhury et al. 2009; Rose and Krishnan 2009; Fashae et al. 2014). Strahler (1964) noted that low drainage density is favored where basin relief is low and vice versa. Smith (1950) classified Dd into five drainage texture (T) viz. less than 2 (very coarse); 2–4 (coarse); 4–6 (moderate); 6–8 (fine); and greater than 8 (very fine). Here, the coarse drainage value indicates highly porous and permeable lithology (Waikar and Nilawar 2014). The river basin possesses dendritic drainage pattern and is generally characterized by a tree-like branching system with homogeneity and uniformity. The drainage density map is classified into five classes using equal-interval classification following Sener et al. (2005) and Hammouri et al. (2012). The classified drainage density map and corresponding rates are shown in Fig. 4 and Table 4, respectively. The drainage pattern in this area indicates that major portion of runoff water remains for long time, and allows more infiltration to recharge the groundwater and, therefore, have more potential for groundwater occurrence.

Rainfall

Rainfall is the major source of groundwater recharge which determines the amount of water that would be available to percolate the groundwater system (Terzer et al. 2013). Rainfall measurement is a point observation and annual rainfall map of the study area is prepared using IDW interpolation from the mean annual rainfall measured at ten existing meteorology stations there. The mean annual rainfall in the area ranges from 1389 to 1715 mm. In the present study, the rainfall map is prepared using equal-interval classification and classified into five classes based on Sener et al. (2005) and Rose and Krishnan (2009). The classified rainfall map and corresponding rates are shown in Fig. 5 and Table 5, respectively. Generally, high annual rainfall distribution indicates the presence of high groundwater potential zones (Sener et al. 2005; Rose and Krishnan 2009; Fashae et al. 2014). Hence, the area with high amount of rainfall is given more weighted value compared to area with low annual rainfall during the analysis of groundwater suitability analysis.

Lithology

Lithology is an important factor that controls the quantity of groundwater occurrence of an area (Bhuvaneshwaran et al. 2015). The lithology has influence on both porosity and permeability of the aquifer (Ayazi et al. 2010; Chowdhury et al. 2009). The major lithological units in the study area are Barind clay residuum (59%), marshy clay and peat including water bodies (19%), alluvial silt and clay (21%), and alluvial sands (1%) of the area. Based on the hydraulic properties of the lithological classes (hydraulic conductivity, transmissivity and specific yield), the lithological classes are ranked as alluvial sand > alluvial silt > alluvial silt and clay > marshy clay and peat > Barind clay residuum. The aquifer properties such as hydraulic conductivity (K), transmissivity (T)

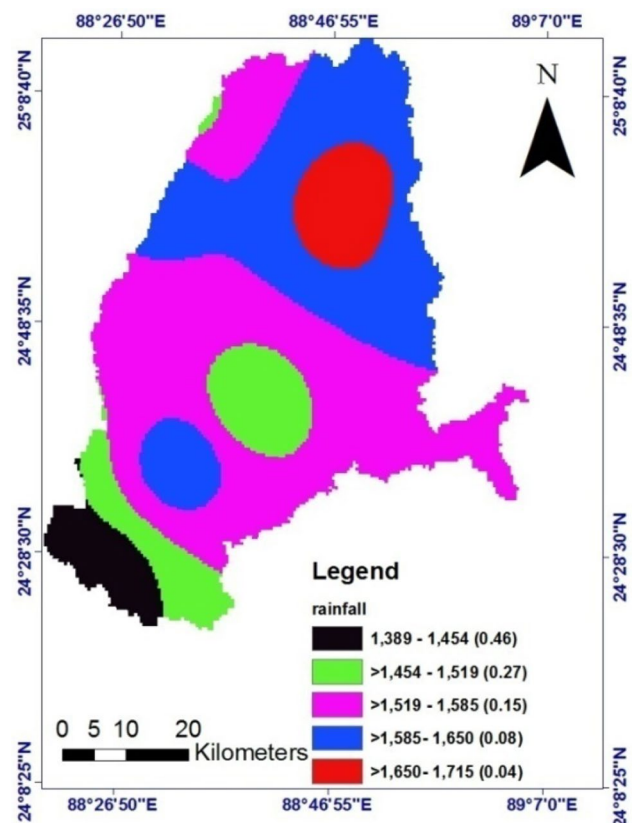
**Fig. 5** Rainfall distribution map of the study area

Table 5 Pair-wise comparison matrix for annual rainfall (mm) classes (CR=0.02)

	1389–1454	> 1454–1519	> 1519–1585	> 1585–1650	> 1650–1715	Rate
1389–1454	1	2	4	6	7	0.46
> 1454–1519		1	2	4	6	0.27
> 1519–1585			1	2	4	0.15
> 1585–1650				1	2	0.08
> 1650–1715					1	0.04

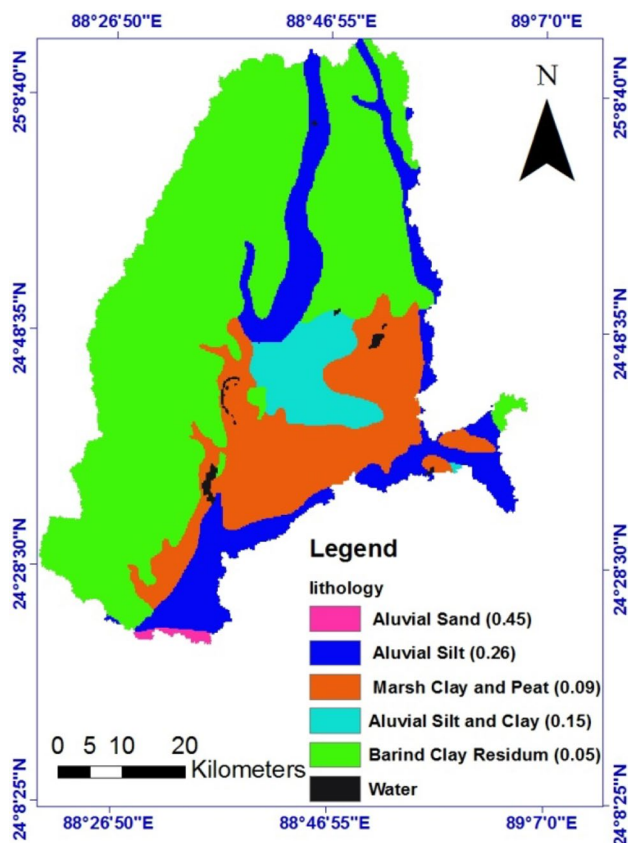
and specific yield (S) values as obtained from pumping test results (IWM 2006) in the area ranges from 25 to 45, 800–2000 m²/day and 0.03–0.18, respectively. The lithology map and rates for lithological classes in the study area are shown in Fig. 6 and Table 6.

Lineament density

Lineament indicates the zones of faulting and fracturing which result in increased secondary porosity and permeability. The area with higher lineament density intensifies infiltration and ultimately groundwater recharge capacity, and provides a good guide for groundwater potentiality study and its exploration (Bhuvaneshwaran et al. 2015). A lineament density map is computed from lineaments produced by edge enhancement of the Landsat ETM+ panchromatic band (band 8) and varies from 0.05 to 0.52 km/km². The lineament density map is prepared based on equal-interval classification (Sener et al. 2005; Hammouri et al. 2012) into five classes. The classified lineament density map and corresponding rates are shown in Fig. 7 and Table 7.

Slope

The slope of an area has an important role in controlling the run-off and hence the infiltration capacity of soil. It is one of the factors controlling the infiltration of water into the subsurface. The higher value of slope causes less infiltration of rainwater through top soil to recharge the groundwater aquifer; hence, it is also an indicator of the suitability for groundwater potentiality. The ranges for slope map classification are based on Berhanu et al. (2013) to characterize the hydrogeological zones and groundwater potentiality. A classified slope map produced shows 62% flat (0–< 3% slope), 35% gentle (3–< 8% slope), 2% moderate (8–< 15% slope) and 1% steep (15–< 30% slope). Flat and gentle slope areas promote infiltration and groundwater recharge, whereas steep slope areas facilitate surface runoff and hence comparatively less infiltration (Jaiswal et al. 2003; Rao and Jugran 2003; Sener et al. 2005; Chowdhury et al. 2009; Machiwal et al. 2011; Hammouri et al. 2012; Fashae et al. 2014). It is observed that the major part of Atrai–Sib river basin comes as gentle to flat which can be designated as the ‘excellent’ category for

**Fig. 6** Lithological map of the study area

groundwater management because of favorable infiltration to maximum time of percolation with runoff. Figure 8 and Table 8 show the classified slope map and the corresponding rates.

Land use/Land cover

The LULC of an area depends on geomorphology, agroecology, climate and human-induced activities, which play an important role in the occurrence and distribution of groundwater. In the present study, the land use pattern and their spatial variation are assessed from satellite data of Landsat-8 December, 2014 (30 m spatial resolution). Here, standard approach is applied using Erdas Imagine 9.1

Table 6 Pair-wise comparison matrix for lithological classes (CR=0.01)

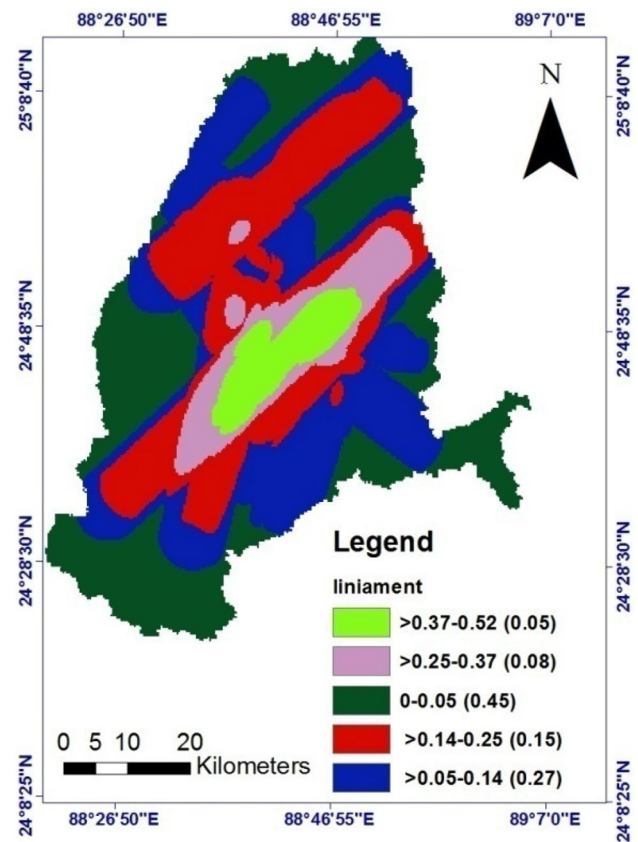
CR	AIS	AISI	AISC	MCP	BCR	Rate
AIS	1	2	3	5	8	0.45
AISI		1	2	3	5	0.26
AISC			1	2	3	0.15
MCP				1	2	0.09
BCR					1	0.05

ALS Alluvial Sand, *ALSI* Alluvial Silt, *ALSC* Alluvial Silt and Clay, *MCP* Marsh Clay and Peat, *BCR* Barind Clay Residuum

software starting from defining of the training sites, extraction of signatures from the image and then classification is made. In present study, the ETM+ image with a band combination of 4 (near infrared), 3 (red) and 2 (green) is used to classify into four LULC classes. The LULC types of the Atrai–Sib river and are identified as cultivated land (95.29%), water body (2.13%), and sand bar (1.99%) and settlement (0.60%). Based on Sener et al. (2005), the ranking of the LULC classes for groundwater potentiality is water body > cultivated land > sand bar > settlement. Here, the degree of cultivation is highly intensified, due to the presence of good groundwater potential. Singh (2014) stated that LULC information is an important factor in groundwater storage and recharge. The classified lineament density map and corresponding rates are shown in Fig. 9 and Table 9. Here, the major part of the area coming under cultivated land supports the need for future river basin development and management. Finally, the Maximum Likelihood Classification (MLC) methods is applied and common land use categories are identified with reference to their water requirement, i.e., cultivated land, settlement, sand bar and water bodies such as wet land, pond, and river.

Delineation of groundwater potential zones

To delineate groundwater potential zones, factors such as geomorphology, drainage density, rainfall, lithology, lineament density, slope and LULC are very important to integrate through RS and GIS technique (Waikar and Nilawar 2014; Ayele et al. 2015; Sisay 2007; Dev 2015; Rose and Krishnan 2009). Groundwater occurs within different hydrogeological environment, and topographic setting which control the groundwater occurrence and exploration for different purposes (Tesfaye 2010). In the present research, the groundwater potentiality zonation of the study area has done by integrating seven thematic layers using weighted overly method of ArcGIS software. The GIS-based multi-criteria evaluation based on AHP is used to compute the rates for the classes and weights, and ranks for thematic layers (Sleight et al. 2016), because all variables have no equal impact in delineating groundwater occurrence and movement (Saaty 1980).

**Fig. 7** Lineament map of the study area

For the seven thematic layers, the consistency ratio (CR) value ranges from 0.01 to 0.09 and values are less than 0.10. According to Saaty (1980), the judgments of the pair-wise comparison within each thematic layer are acceptable. To achieve the priority thematic layers used for delineation of groundwater potential zones in the Atrai–Sib river basin, the pair-wise comparison matrix among the thematic layers is calculated (Table 10). Accordingly, four most influencing factors for delineation of groundwater potential zones (judged from their associated weights) are lithology (38%), lineament density (24%), geomorphology (16%) and slope (10%). The three less influencing factors are drainage density (6%), rainfall

Table 7 Pair-wise comparison matrix for lineament density (km/km^2) classes ($\text{CR}=0.02$)

	0–0.05	>0.05–0.14	>0.14–0.25	>0.25–0.37	>0.37–0.52	Rate
0–0.05	1	2	4	5	7	0.45
>0.05–0.14		1	2	4	5	0.27
>0.14–0.25			1	2	4	0.15
>0.25–0.37				1	2	0.08
>0.37–0.52					1	0.05

(4%), and land use/cover (2%). Here the CR value is 0.08 (less than 0.1) and is acceptable (Saaty1980).

Finally, spatial analysis is involved to combine all thematic layers based on rates for the classes in a layer and weight of thematic layers from the pair-wise comparison. The formula for computing the groundwater potentiality is shown below (Fennta et al. 2015).

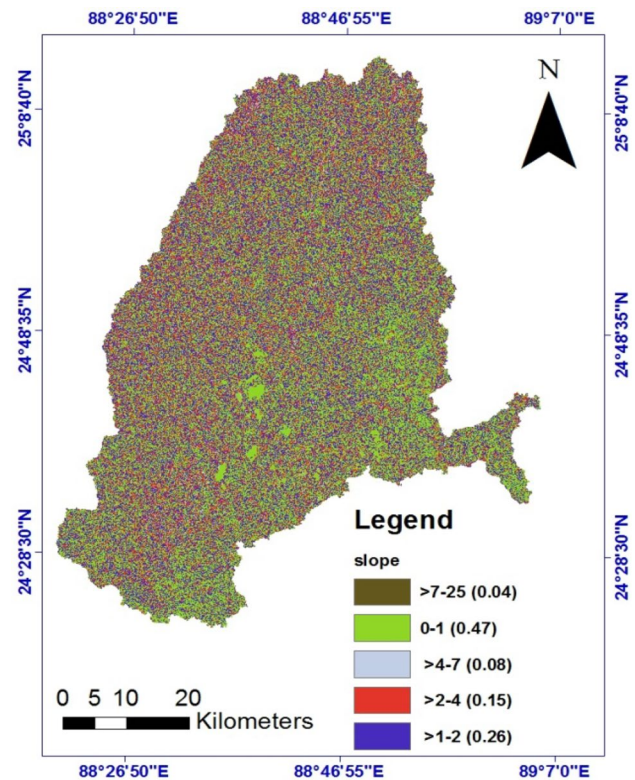
$$\text{GP} = 0.38\text{LD} + 0.24\text{LT} + 0.16\text{GM} + 0.1\text{SL} + 0.06\text{DD} + 0.04\text{RF} + 0.02\text{LU}.$$

where GP is the groundwater potential; LT is the lithology; LD is the lineament density; GM is the geomorphology; SL is the slope; DD is the drainage density; RF is the rainfall; and LULC is the land use/land cover.

The groundwater potentiality zonation map is prepared by the thematic layers and reclassified into five zones, namely, very good, good, moderate, poor and very poor (Fig. 10). The result indicates that 226 km^2 (6% of the study area) has very good groundwater potentiality; 407 km^2 (11%) of the classified as good groundwater potentiality; 720 km^2 (19%) being moderate; 1413 km^2 (38%) is of poor; and 997 km^2 (26%) of the area is under very poor class of groundwater potentiality.

The groundwater potentiality zonation map of the Atrai–Sib river basin shows very good and good zones prominent mostly in the alluvial plains with low geomorphic classes and high drainage density. In these zones, moderate rainfall and flat land area have the high lineament density that has impact on groundwater potentiality which is characterized by cultivated land area with water bodies and human settlements. The surface lithology of the area is characterized by alluvial silt with marshy land characteristics. But the area with moderate to poor–very poor groundwater potentiality zone is lithologically covered by Barind clay and is characterized by moderate to high geomorphology with moderate slope, low to moderate drainage density and low lineament density. This moderate to high rainfall area is also mostly covered by cultivated land.

The result sensitivity analysis of the groundwater potential zonation, i.e., map-removal and single-removal techniques, is given in Tables 11 and 12, respectively. In map-removal technique, high variation of sensitivity index (Table 11) is expected by removal of lineament density from

**Fig. 8** Slope map of the study area

the computation (mean variation index = 2.66%), which could mainly be contributed to the relatively higher weight assigned to the lithology layer (weight = 24%). The groundwater potential map is moderately sensitive to rainfall with mean variation index of 2.56; however, it is less sensitive to LULC (mean = 1.83), geomorphology (mean = 1.73), drainage density (mean = 1.72), slope (mean = 1.48) and lithology (mean = 1.10). The result shows that the variation in index of single thematic layer only depends on the rate and weight itself; not others but the drainage density thematic layer in the index system.

On the other hand, results of single-parameter sensitivity analysis (Table 12) show deviations of the effective weights compared to the empirical weights (Table 10). Similar to the result of the map-removal technique, the single-parameter technique reveals that lineament density as most effective

Table 8 Pair-wise comparison matrix for slope (%) classes (CR=0.09)

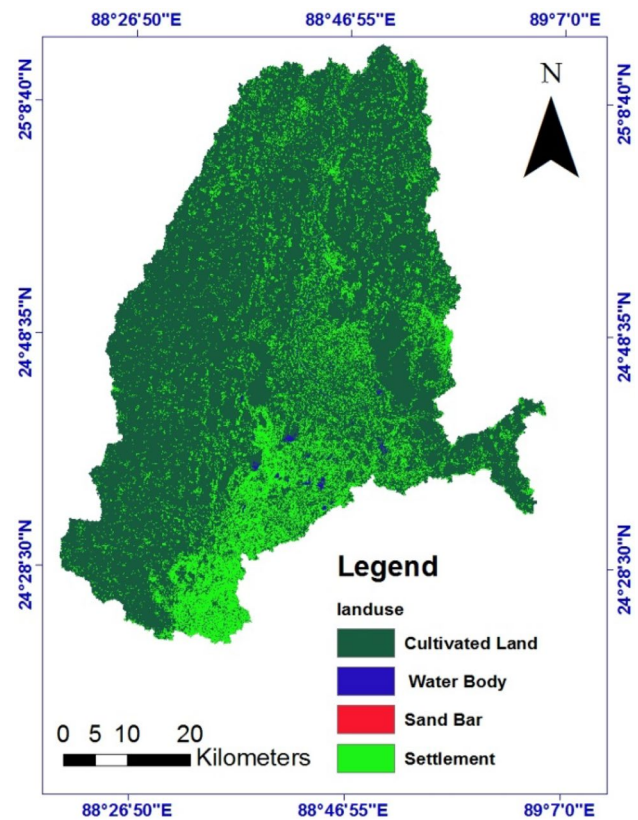
	0–1	> 1–2	> 2–4	> 4–7	> 7–25	Rate
0–1	1	2	4	6	8	0.47
> 1–2		1	2	4	6	0.26
> 2–4			1	2	4	0.15
> 4–7				1	2	0.08
> 7–25					1	0.04

parameter in the groundwater water potentiality study in the Atrai–Sib river basin, where the mean effective weight of 27.13%. It is followed by geomorphology and slope with mean effective weights of 24.43 and 21.32%, respectively, and succeeded by lithology (14.14%), rainfall (5.12%), drainage density (4.09%) and LULC (3.20%) of effective weights with respective empirical weights of 24, 4, 6 and 2%. Here, mean effective values and empirical weights of drainage density, rainfall and LULC are close to each other.

Conclusions

The integrated approach of RS and GIS for delineation of the groundwater potential zones in the Atrai–Sib river basin has given the successful results in terms of minimizing cost, time and labor. Seven different thematic layers such as geomorphology, drainage density, slope and land use and land cover (LULC) are prepared using satellite imageries, topographic maps, and secondary data, and integrated with weighted overlay in GIS to generate groundwater potentiality zonation of the study area. The river basin possesses dendritic drainage pattern and major portion of runoff water allows more infiltration to recharge the groundwater and, therefore, has more potential for groundwater occurrence. The gentle to flat river basin is ‘excellent’ category for groundwater management because of favorable infiltration to maximum time of percolation with runoff.

To delineate the groundwater potentiality of the area, GIS-based multi-criteria evaluation based on Saaty’s AHP is used to compute the rates for the classes in a layer and weights for thematic layers. Then, weighted linear combination (WLC) method is applied to aggregate the thematic layers. Accordingly, very good and good groundwater potential zones occupy 226 and 407 km², respectively, which are respectively 6 and 11% of the study area. The groundwater potentiality zonation map of the river basin shows very good and good zones, prominent mostly in the alluvial plains with low geomorphic classes and high drainage density. These zones of moderate rainfall

**Fig. 9** Land use map of the study area**Table 9** Pair-wise comparison matrix for land use/cover classes (CR=0.02)

	WAT	CL	SB	ST	Rate
WAT	1	2	5	6	0.52
CL		1	2	5	0.28
SB			1	2	0.13
ST				1	0.07

WAT water body, CL Cultivated Land, SB Sand Bar, ST Settlement

Table 10 Pair-wise comparison matrix among thematic layers (CR=0.08)

	LT	LD	GM	SL	DD	RF	LU	Weight
LT	1	2	4	5	6	7	9	0.38
LD		1	2	4	5	6	7	0.24
GM			1	2	4	5	6	0.16
SL				1	2	4	5	0.10
DD					1	2	4	0.60
RF						1	2	0.40
LU							1	0.20

LT lithology, *LD* lineament density, *GM* geomorphology, *SL* slope, *DD* drainage density, *RF* rainfall, *LULC* land use/Land cover

and flat land area have the high lineament density that has impact on groundwater potentiality which is characterized by cultivated land area with water bodies and human settlement. The surface lithology of the area is characterized by alluvial silt with marshy land characteristics. The sensitivity analysis shows that the groundwater potentiality zonation is most sensitive to lineament density with a mean variation index of 2.66% and that of mean effect weight of 27.13%. The effective weights for each thematic layers show variation from the empirical weights with closeness to each other for drainage density, rainfall and land use and land cover (LULC).

Finally, this approach can help to identify quickly groundwater potential zones and can be used as a guideline for integrated water resource management in the study area. Then, by conducting detailed ground hydrogeology and geophysical surveys within the potentiality zones of groundwater, the most appropriate site can be selected for installing tube wells for groundwater in sustainable way.

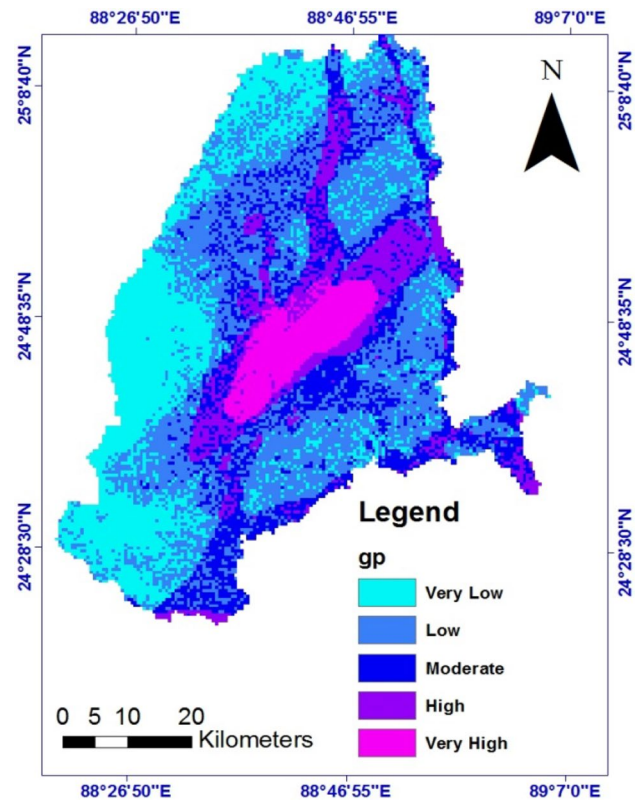
**Fig. 10** Groundwater potentiality zonation map of the study area

Table 11 Statistics of map-removal sensitivity analysis

Layer removed	Variation index (%)			
	Min	Max	Mean	SD
Lineament density	0	9.41	2.66	2.09
Lithology	0	6.91	1.1	0.99
Geomorphology	0	7.63	1.73	1.11
Slope	0	5.44	1.48	1.45
Drainage density	0	2.23	1.72	0.42
Rainfall	0	14.88	2.56	1.8
Land use	0.97	2.31	1.83	0.26

LT lithology, *LD* lineament density, *GM* geomorphology, *SL* slope, *DD* drainage density, *RF* rainfall, *LU* land use/cover, *Max* maximum, *Min* minimum, *SD* standard deviation

Table 12 Statistics of single-parameter sensitivity analysis

Thematic layer	Empirical weight (%)	Effective weight (%)			
		Min	Max	Mean	SD
Lineament density	38	7.79	86.65	27.13	13.49
Lithology	24	3.79	60.82	14.14	9.06
Geomorphology	16	6.58	60.07	24.43	7.01
Slope	10	1.32	46.91	21.32	8.78
Drainage density	6	0.88	23.94	4.09	3.18
Rainfall	4	0.66	19.45	5.12	2.83
Land use	2	0.41	8.99	3.27	1.57

LT lithology, *LD* lineament density, *GM* geomorphology, *SL* slope, *DD* drainage density, *RF* rainfall, *LU* land use/cover, *Max* maximum, *Min* minimum, *SD* standard deviation

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