



Delineation of groundwater potential zones through the integration of remote sensing, geographic information system, and multi-criteria decision-making technique in the sub-Himalayan foothills region, India

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Abstract

The deficiency in groundwater resources worldwide is an alarming issue in the contemporary context, and hence it is significant to analyze the groundwater potential zones (GPZs). The spatial distribution of GPZs assists in identifying the areas with groundwater potentiality and scarcity. The sub-Himalayan foothills region of West Bengal is experiencing high demand for groundwater due to the expansion of anthropogenic activities. Thus, the present work intends to delineate GPZs through integrating remote sensing (RS), geographic information system (GIS), and multi-criteria decision-making (MCDM) technique in the sub-Himalayan foothills district of West Bengal in eastern India. Many predominant thematic criteria ($N=9$), e.g., hydrogeology (HG), elevation (EV), slope (SL), drainage density (DD), lineament density (LD), geomorphology (GEOM), soil (S), annual rainfall (AR), and land-use land cover (LULC), were applied to manifest a reliable outcome. The resulting GPZs map demonstrates ‘moderate’ groundwater potential zone (GPZ) that encompasses all over the parts of the district, covering the highest area (i.e., 73%), while the ‘very good’ GPZ has the lowest extent, observed only in the south-eastern part. Furthermore, micro-level (block-wise) assessment of GPZs has been conducted and illustrated that Mal, Matiali, Rajganj emphasized 8.45%, 6.93%, 4.67%, respectively, areas with ‘low’ groundwater potentiality. In comparison, only Dhupguri block shows very high (only 1.22%) potentiality in the south and south-eastern parts. The produced GPZs map is validated through the acquired data of various dug wells and groundwater fluctuation from the Central Groundwater Board (CGWB). The GPZs were also statistically verified through ROC-AUC assessment, and the result shows that 71.50% area falls under the curve. The findings of the work will be helpful for planners, policy-makers, government agencies, and stakeholders to design sustainable and environment-friendly planning for the concerned region.

Keywords Groundwater potential · Analytical hierarchy process (AHP) · Remote sensing · GIS · Jalpaiguri district

Introduction

Groundwater is a crucial potable water resource used as an important source of water to human beings globally (Abd Manap et al., 2013; Singha et al., 2021). It fulfills the essential demands and sustainable environmental balance and plays an effective role in economic prosperity (IPCC,

2001). The world population, about 2.5 billion, relies primarily on groundwater resources, and in India, the estimated rate of annual withdrawal of groundwater is approximately 230 cubic km (Mukherjee & Singh, 2020; UNESCO, 2015; World Bank, 2012). However, the overexploitation of groundwater resources without proper scientific governance is a frequent threat for the society, as the country’s population around 90% from rural areas and 30% from urban areas solely dependent on it for their drinking, agricultural, and industrial purposes (Agarwal & Garg, 2016). In recent decades due to population booming, enlargement of irrigated area, and advancement in the economy (Mondal & Dalai, 2017), facing enormous changes in groundwater consumption patterns that leads to the pressure in groundwater

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table (Custodio, 2002). Numerous research has revealed that groundwater consumption around the world seems to be under stress due to overexploitation to fulfill rising demand and utilization due to population growth (Pradhan et al., 2021). Groundwater depletion is increasing day by day across the country, influencing a wide range of fields. The adverse impacts of groundwater depletion in India are shifting of the cropping patterns (Shiferaw et al., 2008), increasing the agricultural stress (Sekhri, 2013), reducing the cropping intensity (Jain et al., 2021), increasing the land subsidence tendencies (Choudhury et al., 2018), changing the livelihood strategies and adaptation techniques (Sekhri, 2013), reducing the baseflow of the river (Mukherjee et al., 2018), and hampering the sustainability of the environment. Due to rapid urbanization, urban areas have been converted into massive production hubs (Ozel et al., 2019). Around 99 percent of green covered areas have already been lost in some parts of the Indian metropolitan cities, such as Chennai, Delhi, Kolkata (Arunprakash et al., 2014; Balha et al., 2020; Ray & Shaw, 2016), and these cities are experiencing severe groundwater depletion problem. The Indian economy has surged since the occurrences of the green revolution, but overexploitation of groundwater resources has culminated in dropdown of groundwater levels in the state of Punjab and Haryana (Bhushan, 2017; Joshi & Tyagi, 1991; Singh, 2000). The government has taken many necessary mitigation measures to assess groundwater throughout the country to overcome these problems, emphasizing the areas with special demands. In 1997, the apex government institution (i.e., Central Groundwater Board) was formed to assess the groundwater throughout the country. Its evaluations in 1995, 2004, and 2009 demonstrated there seem to be groundwater management programs at the local level that can promote optimal use of groundwater resources, assist in groundwater quality monitoring, and investigate the groundwater conditions of irrigation command areas, along with expanding efforts in examining hydrological conditions, watershed management, and micro-resource planning (Van Steenberg, 2006).

The integration of remote sensing (RS), geographic information system (GIS), and MCDM technique for mapping the groundwater potential zones (GPZs) are significantly used as the rampant usage of the groundwater resources caused severe crises throughout the world (Allafta et al., 2021; Biswas et al., 2020; Mohammadi-Behzad et al., 2019; Patra et al., 2018). The advancement of technology seems to significantly impact disciplines that incorporate GIS and RS data (Kaya et al., 2019). Parallely, choosing an effective MCDM method for delineating GPZs and recommended management practices at both local and national levels to ensure a sustainable environment is essential (Nithya et al., 2019). Throughout the world, several scholars have taken into consideration many MCDM techniques, viz., analytical

hierarchy process (Boughariou et al., 2021; Huguette et al., 2021; Muavhi et al., 2021; Omosuyi et al., 2021), artificial neural networks (Azimi et al., 2019; Rabet et al., 2020), support vector machine (Rabet et al., 2020), logistic regression (Chen et al., 2018), weights of evidence (Boughariou et al., 2021; Chen et al., 2018), frequency ratio (Boughariou et al., 2021; Muavhi et al., 2021), evidential belief function (Nohani et al., 2017), fuzzy logic (Halder et al., 2020), decision tree (Sachdeva & Kumar, 2021), Shannon's entropy (Forootan & Seyed, 2021), random forest (Rabet et al., 2020; Sachdeva & Kumar, 2021). In the present study, the researchers have applied the AHP method for mapping the GPZs due to the reliability and effectiveness of the technique (Mukherjee & Singh, 2020). The Analytic Hierarchy Process approach, sometimes known as AHP, was developed by Thomas L. Saaty, a professor of mathematics at the University of Pittsburgh. AHP was established as a realistic technique to enhance decision-making in a variety of situations, ranging from individual modern suffering to international conflicts. It is a technique for giving weights to compare particular criteria or alternatives, and it represents a basic notion of subjective assessment. AHP provides a flexible paradigm for problem decision-making, ranking, and prioritization that allows the hierarchy model to be managed and formulated according to specific situations (Horňáková et al., 2021). The application of the AHP method (Vargas, 1990) has been observed in the geographical study, particularly in assessing the natural hazards, viz., landslide susceptibility mapping (Kayastha et al., 2013), mapping the flood susceptibility (Swain et al., 2020), flood risks analysis (Ouma & Tateishi, 2014), and vulnerability of earthquakes (Rashed & Weeks, 2003); site suitability analysis for cities expansion (Parry et al., 2018); agricultural land-use suitability identification (Akinci et al., 2013); evaluating eco-environment quality (Ying et al., 2007); making decisions on natural resources and environmental issues (Schmoldt et al., 2013). Globally, several studies (Aykut, 2021; Murmu et al., 2019; Owolabi et al., 2020; Srinivas et al., 2021) have employed this method for producing significant outcomes. Patra et al. (2018) mapping the GPZs of Hooghly district in the light of the integration of RS and GIS, and AHP MCDM technique for evaluating the sustainability of the concerned region, while Mukherjee and Singh (2020), using the AHP method, examined the GPZs of Birbhum district in West Bengal with 71.50% accuracy. Thus, as a powerful MCDM technique (Pohekar & Ramachandran, 2004; Sahoo et al., 2017), AHP is widely used in assessing GPZs.

The groundwater resources in West Bengal are facing challenges. The State Water Investigation Department (SWID) observed 136 blocks facing problems, where > 20 cm/year the groundwater level has been declined during the pre-monsoonal season (Rudra, 2019). The Central Groundwater Board (CGWB 2019) also identified 76

semi-critical and 1 critical region in the state from their assessment. The present study was conducted in the sub-Himalayan Jalpaiguri district, West Bengal, India. The total annual groundwater recharge of the state has around 2,933,213.98 ham, while the district received 309,405.88 (10.55% of the state) (CGWB 2019). In the district, the per capita water availability was declining sharply. In 1951, it was 18,424 cbm, while it reduced to 9628 cbm in 1971, 6017 cbm in 1991, and 4354 cbm in 2011 (Rudra, 2019). Roy (2011) noticed that the forest area of the district reduced from 80% in 1850 to 28.11% in 2000. The growing unplanned urban centers and massive deforestation to meet the increasing population demand are experiencing large-scale environmental challenges in this sub-Himalayan region. As monsoonal rainfall contributes about 74% of water (CGWB 2019), it is the principal source of groundwater recharge in this region. But during the non-monsoonal season, the groundwater level abruptly falls in this foothills region due to rainfall scarcity, which increases significant socio-economic problems for the inhabitants (Roy et al., 2021). With these backgrounds, the objectives of the study were to highlight the following aspects: (a) mapping the groundwater potentiality of the Jalpaiguri district, a sub-Himalayan foothills region of West Bengal using the incorporation of GIS, RS, and AHP method, (b) micro-level (community development block-wise) identification of areas with the poor (low) and good (high) in occurrences of groundwater.

Materials and methods

Study area

The Jalpaiguri district located in the ‘Duars’ region of the sub-Himalayan West Bengal between the extension of 26° 15′ 47″ N to 26° 59′ 34″ N and 88° 23′ 02″ E to 89° 07′ 30″ E. It has varied terrain (40–581 m) with hills and undulating plains consisting of the Ganga and Brahmaputra River systems. It is bordered with Darjeeling district, and Bhutan are to the north, Koch Bihar and Bangladesh are to the south, Alipurduar district is to the east, and Darjeeling district and Bangladesh are to the west. The entire district is crisscrossed by numerous small and large rivers like the Tista, the Jaldhaka, the Mahananda, the Daina, the Murti, the Lish, the Ghish, the Chel, the Karatoya, etc. The district contains 3386.18 sq. km geographical area, distributed in 7 community development blocks with population density of 701 persons/sq. km (District Profile, Jalpaiguri, 2021). The district is richest in forest resources and well known as the land of 3 T, i.e., ‘Tea, Timber, and Tourism’. Hydrometeorologically, the region falls under a humid sub-tropical climate. The region is characterized by ‘Cwg’ (monsoon type with

dry winter) in respect of Koppen’s scheme of climatic classification, and based on Stamp’s classification it is considered as a region of heavy rainfall. The maximum recorded temperature was 37.9 °C, while the minimum was 7.8 °C. The hottest and coldest month of the region is respectively May and January and having annual humidity is 82%. The annual rainfall of the district generally varies from 3000 to 3500 mm, and December is the driest month, and July is the wettest month. The rainy season of the district is occurred in between June to September. Geologically, the entire district exhibits a wide variety of features, and after Gansser (1964) and Kalvoda (1972), the district has Precambrian, lower Gondwana, Siwalik, and recent to sub-recent formation. In the Quaternary period, the upliftment of the Himalayas resulted in the formation of various faults. Quaternary deposits were observed in the entire study area with two segments: older alluvium and newer alluvium. The location map of the study area manifests the district consists of 8 lithological formations, along with the sub-surface aquifer materials of exploratory wells of CGWB in Salugara, Fata-pukur, Malbazar, and Nagaisuri (Fig. 1).

Selection of thematic layers

In the study, multi-criteria analysis has been considered in the GIS environment. Table 1 represents the factors applied by several researchers in the previous studies for delineating the GPZs. Considering the literatures and opinions from the experts on the local hydrological and groundwater condition, nine geospatial datasets were examined, viz., ‘EV’, ‘SL’, ‘GEOM’, ‘LD’, ‘S’, ‘HG’, ‘AR’, ‘DD’, and ‘LULC’. All data were rectified and projected (UTM zone 45 N WGS-84 datum) in ArcGIS software. These criteria ($N=9$) frameworks the outcome of the whole research. The detailed description of the acquired datasets and methodological framework obtained in this investigation are illustrated in Table 2 and Fig. 2, respectively.

Factors used to delineate GPZs

Hydrogeology (HG)

Hydrogeology (HG) of any region has a dominant control in assessing the nature of the land as well as that reflectance on the groundwater potentiality. As it is the determining factor of infiltration rate and flow, hydrogeology plays a significant role in the occurrence and distribution of groundwater (Tolche, 2021). The varied geological set-up exhibits differences in water holding capacity. The presence of groundwater and its transportation generally depends on the geological formation (Arkoprovo et al., 2012; Saranya & Saravanan, 2020). It also contributes to the percolation process, and hence, the groundwater recharge rate can be affected.

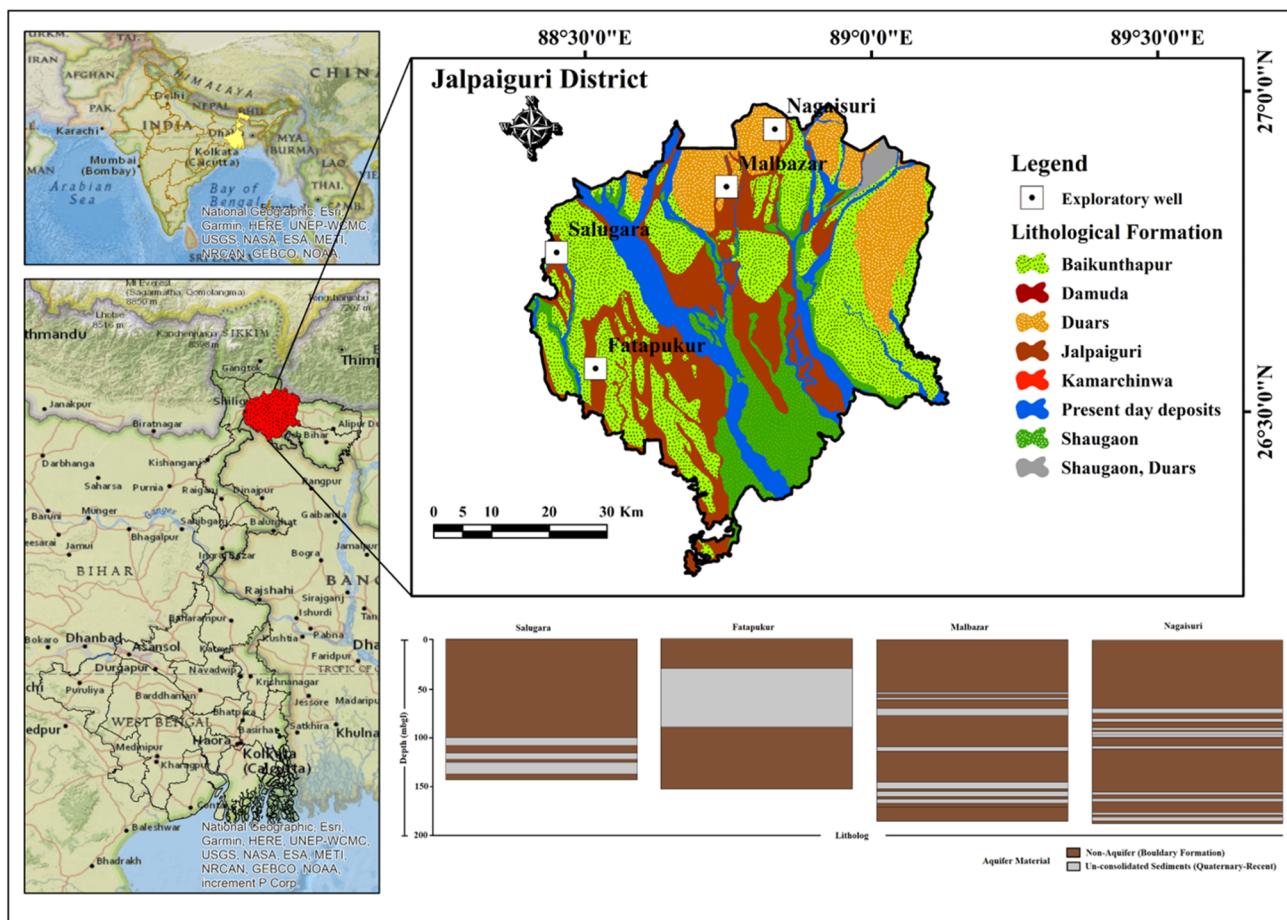


Fig. 1 Location map of the study area, depicting spatial variation in lithological formation and sub-surface litholog-aquifer materials at four distinct places of the district

The entire district is covered with the quaternary deposit, principally formed by silt, sand, clay, lithomargic clay, gravel, and calcareous concentration. Two types of geological formations are mainly found throughout the district: younger and older alluvium, consisting of 61.86% and 38.14% area, respectively, as depicted in Fig. 3a. The principal rivers are the Tista and the Jaldhaka, which usually follow the general slope of the landscape, i.e., from north to the south-east. Here the fluvio-glacial deposits are extensively dissected by the rivers (Roy, 2011). The hydrogeological map of the study area represents that lithologically the area predominated by the zone of granular or fracture, and the thickness of the aquifer generally varies from 50 to 700 m. It also observed that the groundwater yields are expected to range between 200 and 1500 cubic meters per day (Table 3). In the district, the principal aquifer system covered 6227 sq. km area, while alluvium covered 6006 sq. km area, schist covered 37 sq. km area, sandstone covered 80 sq. km area, and limestone covered 104 sq. km area. The water table contour is found from 60 to 100 m above mean sea level, and the flow direction of the groundwater is basically from north to

south. According to CGWB, the groundwater yield potential in the upper parts of the region varies from 1 to 25 L per second, whereas > 40 L per second is observed in the lower parts. The aquifer management plan identifies two artificial recharge priority areas of the district, which are found in the Dhupguri and Nagrakata blocks. Higher ranks were assigned to the rivers, younger alluvium, and lower rank for the older alluvium (Table 7).

Lineament density (LD)

The lineaments study focuses on surface and sub-surface elements; hence, it is a significant determinant of groundwater occurrences (Adiat et al., 2012; Periyasamy et al., 2018). It is the linear elements found like a straight channel of the river, vegetation pattern, and some extent of topographical landforms, and directly indicates the potential zones of groundwater. It can also be present in the form of fracture or faults caused by tectonic activity and allows to percolate water, and impacts the permeability and porosity (Pinto et al., 2017; Saranya & Saravanan,

Table 1 Selection of literatures of conditioning parameters to delineate groundwater potential zones (GPZs)

References	Parameters																
	G	E	SL	LD	DD	LULC	ST	RF	GWL	GM	LI	AQ	PSW	C	TWI	WZT	MNDWI
Kumar et al. (2014)	*		*	*	*	*	*	*									
Shekhar and Pandey (2015)			*	*	*		*	*		*	*					*	
Pinto et al. (2017)		*	*	*	*	*	*	*			*						
Rajasekhar et al. (2018)	*		*	*	*	*	*	*		*							
Mohammadi-Behzad et al. (2019)	*		*	*	*			*									
Nithya et al. (2019)	*		*	*	*	*	*	*		*							
Muniraj et al. (2020)	*		*	*	*	*	*	*		*							
Al-Djazouli et al. (2020)			*	*	*	*		*			*						
Biswas et al. (2020)	*		*		*	*	*	*		*				*	*		*
Achu et al. (2020)			*	*	*	*	*			*	*						
Bera et al. (2020)	*		*	*	*	*	*	*		*				*	*		
Tiwari and Kushwaha (2020)	*		*	*	*	*	*			*							
Saravanan et al. (2020)			*	*	*	*	*	*		*	*						
Saranya and Saravanan (2020)	*	*	*	*	*	*	*	*		*							
Singha et al. (2021)		*	*	*	*	*	*	*	*	*		*	*				

G geology, E elevation, SL slope, LD lineament density, DD drainage density, LULC land-use category, ST stream frequency, RF rainfall, GWL groundwater level, GM geomorphology, LI lithology, AQ aquifer, PSW proximity to surface water, C curvature, TWI topographic wetness index, WZT weathered zone thickness, MNDWI modified normalized difference water index

Table 2 Source and description of the parameters used in the study

Parameters	Descriptions	Source
Geomorphology (GEOM)	Digitized from vector layer	Geological Survey of India (GSI) https://www.gsi.gov.in
Soil (S)	Digital soil map of the world (ESRI shapefile)	Food and Agriculture Organization (FAO) http://www.fao.org
Land use land cover (LULC)	Landsat 8 OLI/TIRS, (30 m*30 m)	United States Geological Survey (USGS) https://earthexplorer.usgs.gov
Lineament (LD)	Vector layer, (1:1,091,958)	Geological Survey of India (GSI) https://www.gsi.gov.in
Hydrogeology (HG)	Digitized from raster data	Central Ground Water Board (CGWB) http://wbwriid.gov.in
Annual rainfall (AR)	Gridded rainfall (0.25 × 0.25) NetCDF File	India Meteorological Department (IMD) https://www.imdpune.gov.in
Slope (SL)	Derived from ASTER DEM (30 m*30 m) using ArcGIS	United States Geological Survey (USGS) https://earthexplorer.usgs.gov
Drainage density (DD)	Derived from ASTER DEM (30 m*30 m) using fill, flow accumulation, line density tool in ArcGIS	United States Geological Survey (USGS) https://earthexplorer.usgs.gov
Elevation (EV)	Derived from ASTER DEM (30 m*30 m) using ArcGIS	United States Geological Survey (USGS) https://earthexplorer.usgs.gov
Groundwater	Sub-surface aquifer characteristics of exploratory wells, groundwater level data of 11 observed wells and groundwater fluctuation data (in mbgl),	Central Ground Water Board (CGWB) http://cgwb.gov.in/
Lithology	Digital lithological map of the district	Geological Survey of India (GSI) https://bhukosh.gsi.gov.in/

2020); thus, the lineament in a hydrological context is always relevant (Solomon & Quiel, 2006). It is observed that the groundwater potentiality is found comparatively

higher in the case of high lineament zones (Abd Manap et al., 2013). The lineament data has been extracted from

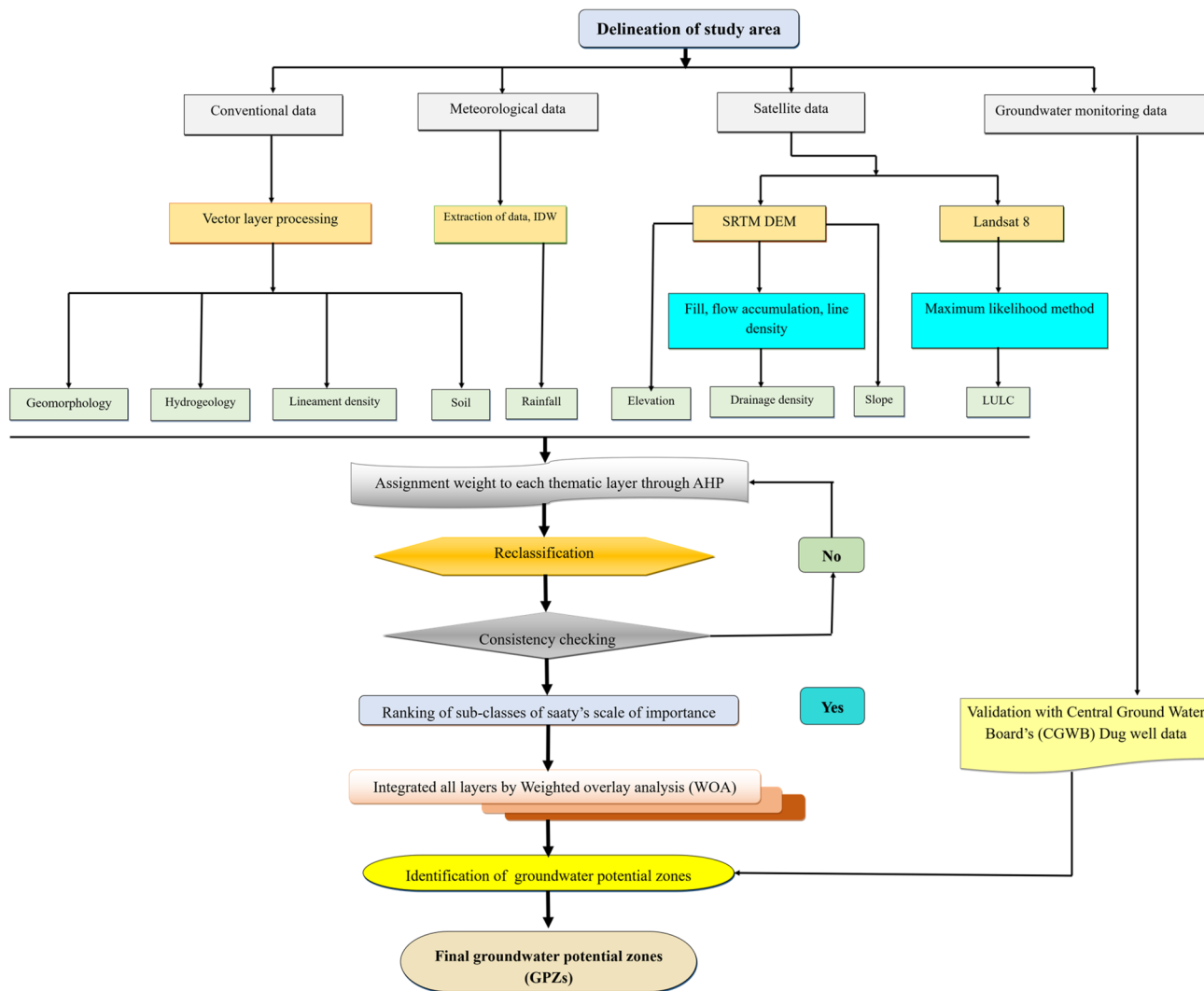


Fig. 2 Methodological framework for delineation of groundwater potential zones (GPZs) of the study area

the GSI, and using ArcGIS ‘line density’ tool, the ‘LD’ map was prepared, as shown in Fig. 3b. The ‘LD’ value varies from 0 to 0.41 km/sq. km. The ‘very high’ ‘LD’ zone (0.28–0.41) was found in the northern part with only 0.33% of areal coverage, whereas the ‘high’ ‘LD’ zone (0.18–0.28) covered 6.79% area, ‘moderate’ ‘LD’ zone (0.11–0.18) covered 7.54% area, ‘low’ ‘LD’ zone (0.03–0.11) covered 6.89% area, and ‘very low’ ‘LD’ zone (0–0.03) covered the maximum part (78.45% area) of the region. Using RockWorks 17 software, the rose diagram of the lineament was produced to show the direction of lineaments and their spatial pattern of distribution. The dominant trend in the study area is NW–SE direction; others were NE–SW, N–S, etc. Higher ‘LD’ classes were assigned higher ranks for ranking, and lower ‘LD’ classes were considered lower ranks (Table 7).

Elevation (EV)

The elevation (EV) has a major function in delineating the groundwater potentiality (Sachdeva & Kumar, 2021). The ‘EV’ map depicted the ruggedness, undulations of the topography and also a connection with the climatic variables (Saranya & Saravanan, 2020; Shafizadeh-Moghadam et al., 2018). The areas with higher elevation reflect the higher runoff and lower infiltration rate, while the lower elevated regions show higher groundwater recharge as well as groundwater potentiality (Singha et al., 2021). The topography of the region exhibits a mixed look between the hilly rugged area with undulating and flat plains (DCH 2011). Roy (2011) topographically divided the region into three distinct divisions, i.e., hills, piedmonts, and plains. The entire region demarcated with five physiographic classes varies from 40 to 581 m

Fig. 3 Thematic layers of nine selected parameters for delineating groundwater potential zones (GPZs) of the Jalpaiguri district **a** Hydrogeological map, **b** Lineament density map, **c** Elevation map, **d** Slope map, **e** Annual rainfall map, **f** Geomorphological map, **g** Soil map, **h** Drainage density map, **i** LULC map

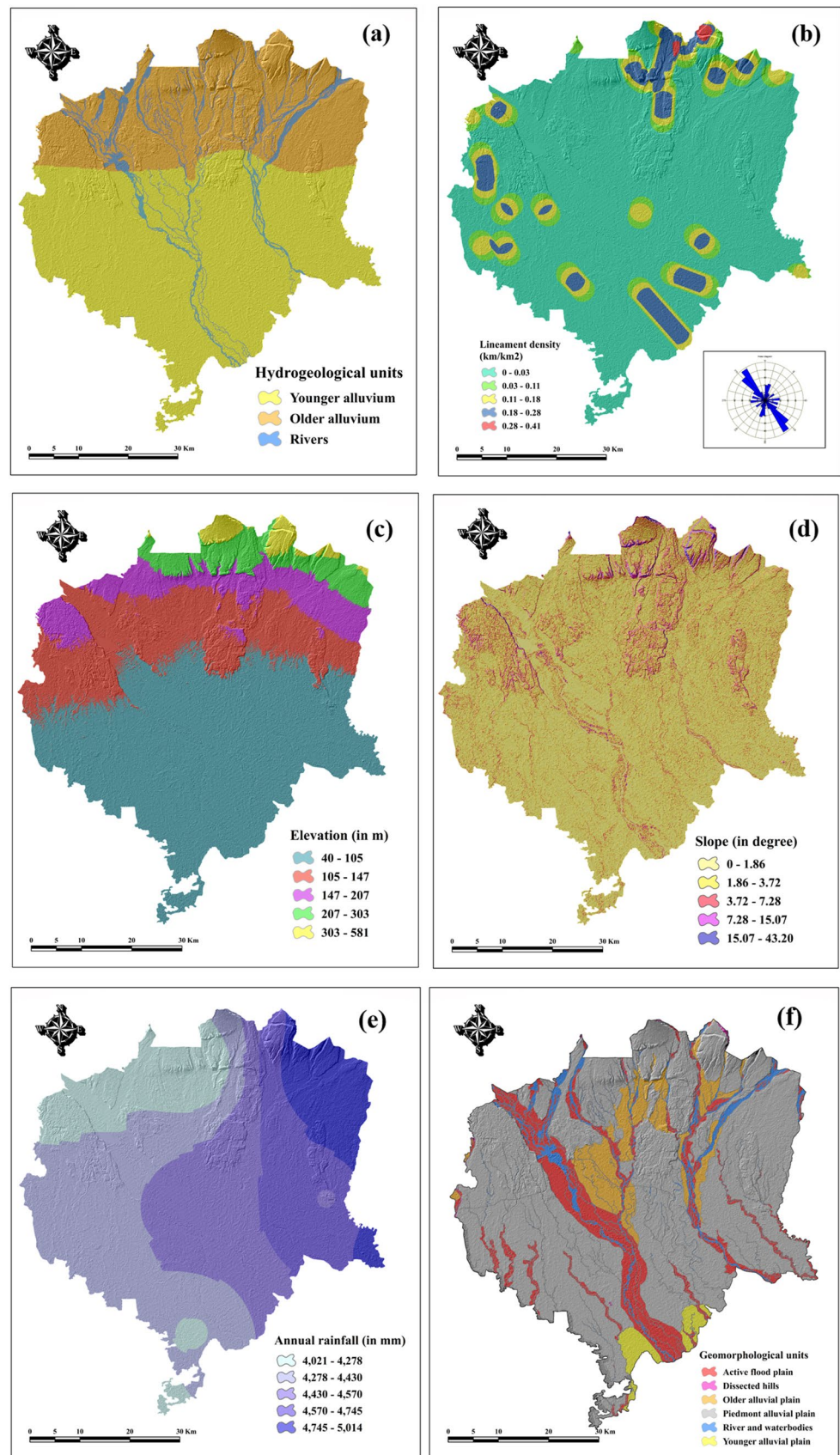


Fig. 3 (continued)

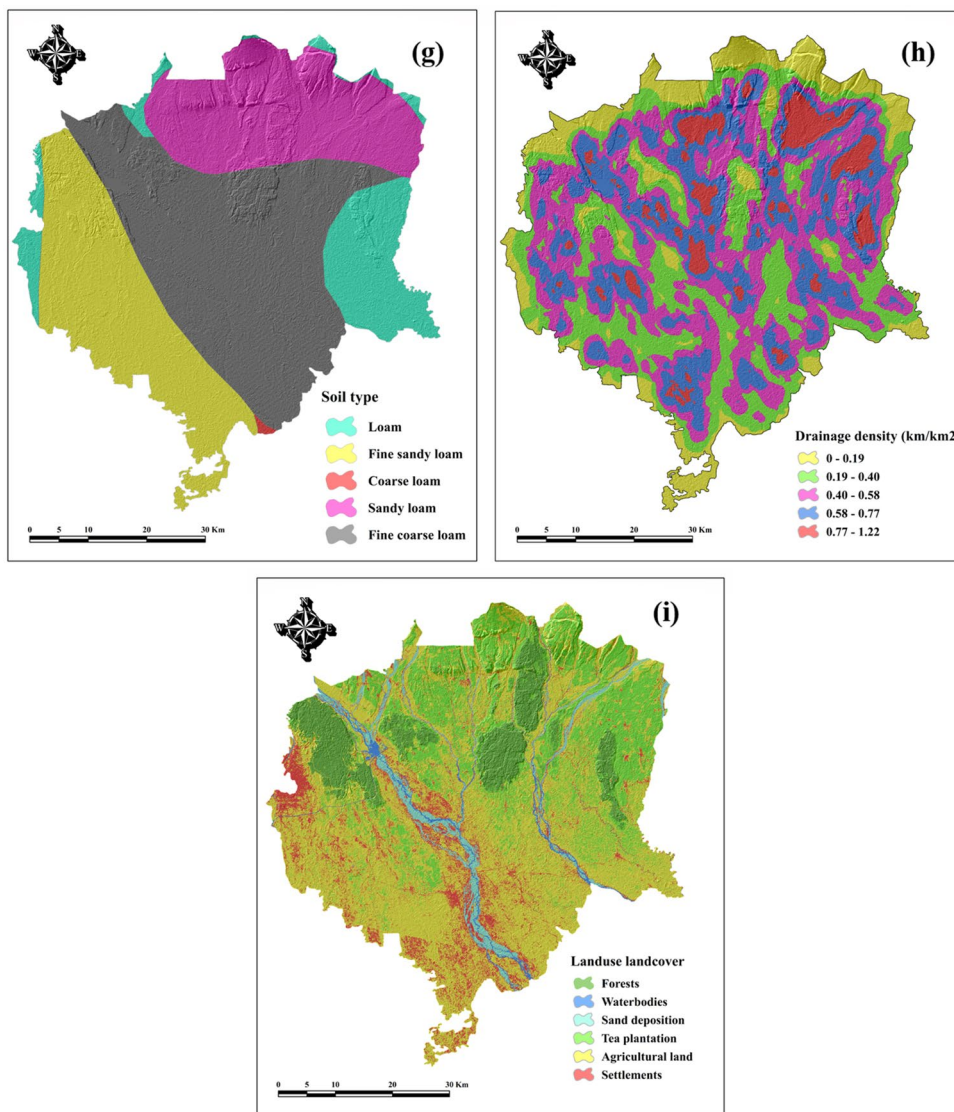


Table 3 Rock type, lithology, aquifer and hydrogeology of the study area based on CGWB and GSI

Rock type	Age	Lithological characteristics	Aquifer characteristics	Hydrogeological characteristics
Older alluvium (silt/sand/gravel/ lithomargic clay)	Quaternary	Granular/fracture zones were found between 15 and 400 m below ground level	Aquifer/weathered zone thickness ranges from 50 to 700 m	Groundwater yields are range from 200 to 1500 cubic meters per day
Younger alluvium (clay/silt/sand/ calcareous concretion)				

(Fig. 3c). As the alluvial plain areas covered the highest area (around 53.73%), therefore maximum precipitation easily infiltrates and enriches the groundwater level during the rainy season. The plains areas have massive aggradational and perennial behavior of the rivers. Hilly rugged topography found in the extreme northern portion

covered 2.39% area. Here maximum ranks are assigned for the plain region, and then it decreases for the higher elevated region (Table 7).

Slope (SL)

The slope (SL) is an important parameter in assessing groundwater potentiality due to its effect on the hydrological cycle (Mosavi et al., 2021). The infiltration and run-off capacity have been directly influenced by it. The steeper slope always accelerates the run-off rate and decelerates the infiltration capacity, hence poorly recharging the groundwater. In gently sloping land, the infiltration rate is high due to adequate time for rainwater to percolate (Gupta et al., 2018; Mosavi et al., 2021; Patra et al., 2018). Thus, the 'SL' of any area plays an inverse relationship to the groundwater recharge (Prasad et al., 2008). In case of 'SL' map five classes here identified (Fig. 3d), i.e., (a) 0° – 1.86° (48.88%), (b) 1.86° – 3.72° (35.69%), (c) 3.72° – 7.28° (13.05%), (d) 7.28° – 15.07° (2.02%), and (e) 15.07° – 43.20° (0.36%). The maximum portion of the district is covered $< 8^{\circ}$ slope, i.e., the flat to gently sloping land. These lands are suitable for groundwater penetration and are characterized by very high to medium prospects in groundwater recharge. In contrast, the steeply sloping land observed in the north-western part has lower prospects. In the distribution of ranks, lower 'SL' classes were assigned higher ranks, and higher 'SL' classes were considered lower ranks (Table 7).

Annual rainfall (AR)

Rainfall is directly related to groundwater recharge (Patra et al., 2018) and hence, is recognized as an essential parameter. It exaggerates the hydrological cycle and thus influences the groundwater potentiality. Several studies exhibit the correlation between rainfall and occurrences of groundwater (Dey et al., 2020; Wang et al., 2015). In this sub-Himalayan district, the south-west monsoon accounts for 80–85% of rainfall throughout the rainy season (June–September). This region stands for one of the rainiest areas along the Himalayan margin (Roy, 2011). The 'AR' map of this region is produced, applying the IDW (Inverse Distance Weighting) technique in ArcGIS based on the extracting data provided by IMD (India Meteorological Department). The spatial variation in the 'AR' pattern is shown in Fig. 3e. Generally, the tendency of the rainfall is decreasing from the east to the west in the region. It varies from 4021.72 to 5014.06 mm and classified into five groups, like (a) 4021.72–4278.56 mm (15.44%), (b) 4278.56–4430.33 mm (34.86%), (c) 4430.33–4570.43 mm (23.12%), (d) 4570.43–4745.55 mm (16.16%), and (e) 4745.55–5014.06 mm (10.42%). Higher rainfall classes were assigned higher ranks, while lower rainfall classes were considered lower ranks, as shown in Table 7.

Geomorphology (GEOM)

The geomorphological features help in understanding the controlling factors of the groundwater (Patra et al., 2018), and it also assists in portraying mechanisms with groundwater recharge (Prasad et al., 2008; Swain, 2015). It is observed the flood plains region has higher groundwater potentiality than the areas with ridges and valleys (Nithya et al., 2019). The geomorphological data of the concerned region has been collected from the GSI and using ArcGIS depicted in Fig. 3f. The entire region is mainly composed of piedmont alluvial plain (68.82%), older flood plain (13.56%), dissected hills (8.20%), younger alluvial plain (7.06%), active flood plain (2.12%), rivers and water bodies (0.24%). As here, the maximum area is covered with alluvial plains; hence, groundwater's prospect is generally good. Dissected hills region having poor groundwater potentiality resulted from high runoff and low recharge capacity. In ranking, rivers and water bodies, active floodplains were assigned higher ranks, and dissected hills were considered lower rank (Table 7).

Soil (S)

Soil is another critical element that influences groundwater potentiality. The physical properties of soil, like, texture, moisture, permeability, porosity, structure, affect the rate of infiltration of the land (Chakraborty et al., 2020; Pal et al., 2020). The soil map of the present study area has been produced using the FAO world soil data, and the classified map was named according to its texture. The data revealed that the region exhibits five major soil classes (Fig. 3g), where fine coarse loam soil covered the highest area (40.30%), followed by fine sandy loam (24.25%), sandy loam (22.43%). Due to higher porosity and permeability, sandy soils are favorable to groundwater contamination compared to others (Nasir et al., 2018; Patra et al., 2018). Ranks were assigned to different soil types based on their structure and capacity to hold water. Higher ranks were allocated to the fine coarse loam, coarse loam, and lower ranks for the clay and sandy loam (Table 7).

Drainage density (DD)

Drainages have played a vital role in the determination of GPZs. Usually, lower stream number per unit area represents lower runoff and higher infiltration, and thus, as a consequence, rich groundwater potential zones are developed (Magesh et al., 2012; Mohammadi-Behzad et al., 2019), but in exceptions, where alluvial depositions, groundwater might be expected to concentrate there (Diaz-Alcaide and Martinez-Santos 2019). The prepared 'DD' map has been represented in Fig. 3h. High 'DD' areas are considered low ranks and low 'DD' areas as high ranks, as shown in Table 7.

Historically, the district experienced significant changes in its river system, like the mighty Tista was earlier flowing into the Ganga through the Karatoya, the Atreyee, and the Punarbhava, but after 1787 the Tista changed its course and merged with the Brahmaputra River (Mukherjee, 1996). Parallely, many small rivers had frequent channel migration behavior due to the physical settings of the area. However, during monsoonal time almost every year, the low-lying riparian areas are inundated by these rivers.

Land use land cover (LULC)

The land-use land cover (LULC) was used to detect the stress on groundwater due to increasing anthropogenic activities. The spatial distribution of land-use pattern affects groundwater recharge, as areas with fallow land, built-up are regarded as poor sources of groundwater recharge, whereas the areas with cultivable lands, vegetation cover, and water bodies are considered as good sources (Patra et al., 2018). In this study, the LULC map was produced using the maximum likelihood supervised classification technique in ArcGIS. Six categories of land use have been identified, i.e., (i) forests, (ii) water bodies, (iii) sand deposition, (iv) tea plantations, (v) agricultural lands, and (vi) settlements. The agricultural land represents the highest area (50.30%), while tea plantations represent 23.09%, forest land represents 10.69%, settlements represent 10.23%, illustrated in Fig. 3i. In the Jalpaiguri district, the livelihood of the inhabitants is mainly dependent on agriculture. Higher ranks were allocated to the water bodies, sand deposition, and agricultural lands, and lower ranks to the settlements, tea plantations (Table 7).

The AHP method and weighting the indicators

In the present study, the AHP method was considered to detect regional GPZs. It is generally used by scholars in terms of weighting or rating the components and their categories (Kumar & Anbalagan, 2016), and it is an effective approach to solve complex problems (Souissi et al., 2020). AHP is a systematic MCDM approach that creates an eigenvalue, pair-wise comparison matrix and uses experts' knowledge to establish the rank and weights. This strategy is best suited for making decisions in an issue with multiple

variables. This procedure entails the creation of a pair-wise matrix in which the weights of each parameter are set, considering the relative relevance of all other parameters (Saaty, 2008).

To estimate the GPZs of the Jalpaiguri district, the researchers have selected nine thematic parameters, and then the weights were given to all parameters compared to other parameters. As a result, a pair-wise comparison matrix (PCM) has been computed by experts' opinions as well as field experiences. Based on their relative relevance, each criterion was given a rank from 1 to 9, as illustrated in Table 4. The value 1 is organized diagonally in this matrix, with an equal number of columns and rows. The relative relevance of the two criteria is determined in each row. The relevance of a criteria in relation to nine other criteria in the column is represented by the first row of the matrix. The rows express the inverse value of every indicator and its relative importance to other indicators; for example, if rainfall is more important than LULC, therefore, rainfall is represented by value 1, while LULC is represented by value 2; consequently, LULC is represented by value ½ in the next row (Table 5) (Bera et al., 2020). The sub-classes of selected indicators were given using Saaty's relative importance scale.

As Saaty (1980) suggested that the consistency index (CI) and consistency ratio (CR) were calculated following normalization to ensure that the pair-wise matrix was homogeneous. The steps are used in the present study:

Step-I Using the eigenvector approach, the principal eigenvalue (λ) was computed.

Step-II The following equation (Saaty, 1980) was used to determine the CI:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (1)$$

where n represents the total no of parameter, and λ_{\max} represents the principal eigenvalue, which can be explained as follows:

$$\lambda_{\max} = \sum_{j=1}^n a_{ij} \frac{w_j}{w_i} = n \quad (2)$$

Step-III CR was determined and expressed as follows (Saaty, 1980):

Table 4 Description of the scale of relative importance (Saaty, 1980)

Scale	Degree of performances	Descriptions
1	Equally important	The contribution of the two factors is equally important
3	Slightly important	Experiences and judgment slightly tend to a certain factor
5	Quite important	Experiences and judgment strongly tend to a certain factor
7	Extremely important	Experiences and judgment extremely tend to a certain factor
9	Absolutely important	There is sufficient evidence for absolutely tending to a certain factor
2, 4, 6, 8	Intermediate value	In between two judgements

Table 5 Pair-wise comparison matrix of all selected parameters developed for AHP based GPZs

Parameters	GEOM	LD	DD	SL	EV	S	LULC	AR	HG
GEOM	1	2	3	5	7	8	9	2	2
LD	1/2	1	2	3	4	8	7	1/2	3
DD	1/3	1/2	1	3	7	7	7	1/3	2
SL	1/5	1/3	1/3	1	5	5	5	1/3	1
EV	1/7	1/4	1/7	1/5	1	7	4	1/4	1/3
S	1/8	1/8	1/7	1/5	1/7	1	3	1/5	1/6
LULC	1/9	1/7	1/7	1/5	1/4	1/3	1	1/7	1/4
AR	1/5	1/3	3	3	4	5	7	1	1
HG	1/5	1/3	1/2	1	3	6	4	1	1

GEOM geomorphology, LD lineament density, DD drainage density, SL slope, EV elevation, S soil, LULC land-use land cover, AR annual rainfall, HG hydrogeology

$$CR = \frac{CI}{RI} \tag{3}$$

where CI stands for the consistency index, and RI stands for the random index.

The CR value of 0.10, according to Saaty (1990), is sufficient to perform the research. Furthermore, if the CR value is > 0.10, the analysis must be modified to identify the source of the matrix’s inconsistency. If the CR value is zero, the PCM is perfectly accurate. However, the CR value in the investigation is 0.09 (Table 6), which is < 0.10, indicating that the analysis can proceed. For further analysis, all vector maps were transformed into raster format, and by assigning their weights (Table 7), all criteria maps were integrated.

Delineation of GPZs

The groundwater potential index (GWPI) is a tool for predicting GPZs in a given region. It is a dimensionless metric for delineating prospective groundwater tract, and hence, in this study, the GPZs map was produced using the following

formula (Berhanu & Hatiye, 2020; Kumar & Krishna, 2018; Mohammadi-Behzad et al., 2019; Prasad et al., 2008).

$$GPZsM = (MP1w \times SP1r) + (MP2w \times SP2r) + (MP3w \times SP3r) + (MP4w \times SP4r) + (MP5w \times SP5r) + (MP6w \times SP6r) + (MP7w \times SP7r) + (MP8w \times SP8r) + (MP9w \times SP9r) \tag{4}$$

where GPZsM represents groundwater potential zones mapping, MP1 – MP9 represents the thematic layer map of the main parameter, w represents the weight of the main parameter, SP1 – SP9 represents the sub-parameter of each thematic layer map, and r represents class raking of the sub-parameter map.

Validation of GPZs

To verify the accuracy of the produced GPZs, it should be compared with the real groundwater data of the concerned region (Mohammadi-Behzad et al., 2019; Mukherjee &

Table 6 Calculating the normalized weights for thematic layers

Parameters	GEOM	LD	DD	SL	EV	S	LULC	AR	HG	WEIGHT
GEOM	0.254	0.324	0.399	0.395	0.343	0.200	0.162	0.366	0.194	0.254
LD	0.127	0.162	0.266	0.237	0.196	0.200	0.126	0.092	0.291	0.162
DD	0.084	0.081	0.133	0.237	0.343	0.175	0.126	0.060	0.194	0.133
SLOP	0.051	0.053	0.044	0.079	0.245	0.125	0.090	0.060	0.097	0.079
EV	0.036	0.041	0.019	0.016	0.049	0.175	0.072	0.046	0.032	0.049
SOIL	0.030	0.021	0.019	0.016	0.007	0.025	0.054	0.037	0.016	0.025
LULC	0.028	0.023	0.019	0.016	0.012	0.008	0.018	0.026	0.024	0.018
AR	0.127	0.324	0.399	0.237	0.196	0.125	0.126	0.183	0.194	0.183
HG	0.127	0.053	0.067	0.079	0.147	0.150	0.072	0.183	0.097	0.097

Consistency Ratio (CR) = 0.09 < 0.1

GEOM geomorphology, LD lineament density, DD drainage density, SL slope, EV elevation, S soil, LULC land-use land cover, AR annual rainfall, HG hydrogeology

Table 7 Assigning rank and normalized weights for all nine thematic parameters for delineating GPZs of Jalpaiguri district

Parameters	Class	Level of potentiality	Rank	Normalized weight	Influence (%)
Geomorphology	River and waterbody	Very good	5	0.25	25
	Active flood plain	Very good	5		
	Younger alluvial plain	Good	4		
	Older alluvial plain	Moderately good	3		
	Piedmont alluvial plain	Moderate	2		
	Dissected hills	Poor	1		
Annual rainfall (mm)	4021–4278	Poor	1	0.18	18
	4278–4430	Moderate	2		
	4430–4570	Moderately good	3		
	4570–4745	Good	4		
	4745–5014	Very good	5		
Lineament density (km/km ²)	0–0.03	Very poor	1	0.16	16
	0.03–0.11	Poor	2		
	0.11–0.18	Moderate	3		
	0.18–0.28	Good	4		
	0.28–0.46	Very good	5		
Drainage density (km/km ²)	0–0.19	Very good	5	0.13	13
	0.19–0.40	Good	4		
	0.40–0.58	Moderately good	4		
	0.58–0.77	Moderate	3		
	0.77–1.22	Poor	2		
Slop (°)	0–1.86	Very good	5	0.08	8
	1.86–3.72	Good	4		
	3.72–7.28	Moderate	3		
	7.28–15.07	Poor	2		
	15.07–43.20	Very poor	1		
Elevation (m)	40–105	Very good	5	0.05	5
	105–147	Good	4		
	147–207	Moderate	3		
	207–303	Poor	2		
	303–581	Very poor	1		
LULC	Water bodies	Very good	5	0.02	2
	Sand deposits	Very good	5		
	Agricultural lands	Good	4		
	Forests	Moderately good	3		
	Tea gardens	Moderate	2		
	Settlements	Poor	1		
Soil	Fine coarse loam	Very good	4	0.03	3
	Coarse loam	Good	3		
	Loam	Good	3		
	Fine sandy loam	Moderate	2		
	Sandy loam	Moderate	2		
	clay	Poor	1		
Hydrogeology	Rivers	Good	5	0.10	10
	Younger alluvium	Moderate	4		
	Older alluvium	Poor	2		

Singh, 2020). For this purpose, firstly, pre-monsoonal and monsoonal groundwater level data from CGWB was collected to show the spatial pattern of fluctuation (CGWB 2020). Along with 11 observed wells of the CGWB across the district were selected for cross-checked with the produced GPZs map, as in the recent time several scholars used these technique to validate the result, viz., Patra et al. (2018); Saranya and Saravanan (2020); Saravanan et al. (2020). The ROC-AUC study has been carried out to statistically verify the results using the dug well data (2018) of the CGWB (Table 8).

Results and discussion

GPZs

The produced GPZs map exhibited variations throughout the region. The study revealed four distinct zones, specifically, ‘low’, ‘moderate’, ‘high’, and ‘very high’ GPZs, determined by nine different parameters (Fig. 4). In the present study, the weights of the selected parameters are assigned based on expert-based opinions (Mukherjee & Singh, 2020; Patra et al., 2018; Saranya & Saravanan, 2020; Singha et al., 2021). The assigned weights of selected parameters have been illustrated in Table 7. The most influencing factors, (i.e., > 70%) in determining the groundwater potentiality, are the ‘GEOM’ (25%), ‘AR’ (18%), ‘LD’ (16%), and ‘DD’ (13%). Moderate weights were assigned to the ‘HG’ (10%) and ‘SL’ (8%), while lower weights were given to the ‘EV’ (5%), ‘S’ (3%), and ‘LULC’ (2%).

Around 0.10% area of the district has ‘very high’ groundwater potentiality, observed only in the extreme south-eastern part due to the high level of the groundwater table. Here the source of groundwater recharge is the rivers as well as the water bodies. These are the active floodplain region, and here the rate of annual rainfall is about 5000 mm. The areal spread of the ‘high’ GPZ is approximately 24.05%, and it is found in the entire region, specifically in the active floodplains along the rivers, viz., the Tista, the Jaldhaka. Mainly the alluvial tracts, fine loamy soil, high groundwater retaining capacity are the characteristics of these areas. Here the run-off rate is low, and infiltration is more compared to hilly areas. Subsequently, the ‘moderate’ GPZ covered the 73% area, including highlands, piedmont alluvial plains, valleys, moderate to gentle sloping lands. The ‘low’ GPZ is illustrated in the regions of rugged hills, steep slopes, dense forests. It is located in the extreme north, north-western parts of the region. About 2.85% area consisting this zone, and it has low groundwater prospects. Table 9 shows the distribution of different categories of groundwater potentiality in the district.

In the micro-level analysis (Table 10), it is observed that only the Dhugguri block has ‘very high’ (1.24%) potentiality in the occurrences of groundwater, observed in the south and south-eastern parts. The blocks with threat areas, i.e., ‘low’ GPZ was found in the northern, north-eastern, and central parts of the Mal block (‘low’ potentiality: 8.40%); western, central, and north-western parts of the Matiali block (‘low’ potentiality: 6.93%); and northern and north-western parts of the Rajganj block (‘low’ potentiality: 4.67%). Maynaguri block represents maximum (40%) ‘high’ GPZ, frequently

Table 8 Site-wise dug well data of the post-monsoon rabi (POMRB) season of CGWB for the year 2018 in Jalpaiguri district

Latitude	Longitude	Site name	Site type	Well code	POMRB (mbgl)
26.8972	88.9083	Nagrakata I	Dug Well	W29691	10.51
26.5417	88.5389	Rajganj	Dug Well	W11206	6.38
26.4469	88.6569	Berubari	Dug Well	W10532	2.37
26.5219	88.6667	Raninagar	Dug Well	W11207	2.47
26.6125	88.7806	Maynaguri	Dug Well	W10548	3.36
26.4422	88.6961	Konpakuri	Dug Well	W10545	2.61
26.5125	88.7417	Jalpaiguri	Dug Well	W10540	2.79
26.6167	88.4847	Hathi More	Dug Well	W10538	6.4
26.6194	88.4411	Jatiakhalimore	Dug Well	W10541	3.18
26.5575	88.4558	Gadra	Dug Well	W10535	3.61
26.7556	88.7472	Lataguri	Dug Well	W10546	2.84
26.8986	88.7875	Chalsa	Dug Well	W10533	4.3
26.8592	88.9117	Khairbari	Dug Well	W10544	4.28
26.8972	88.9083	Nagrakata	Dug Well	W10549	7.71
26.81	88.4706	Salugara	Dug Well	W33279	9.3
26.5472	88.6086	Dus Doroga	Dug Well	W29611	2.94
26.5717	88.54	Fatapukur	Dug Well	W29625	4.18
26.8644	88.6256	Odlabari	Dug Well	W29684	1.93

Fig. 4 Groundwater potential zones (GPZs) of the Jalpaiguri district

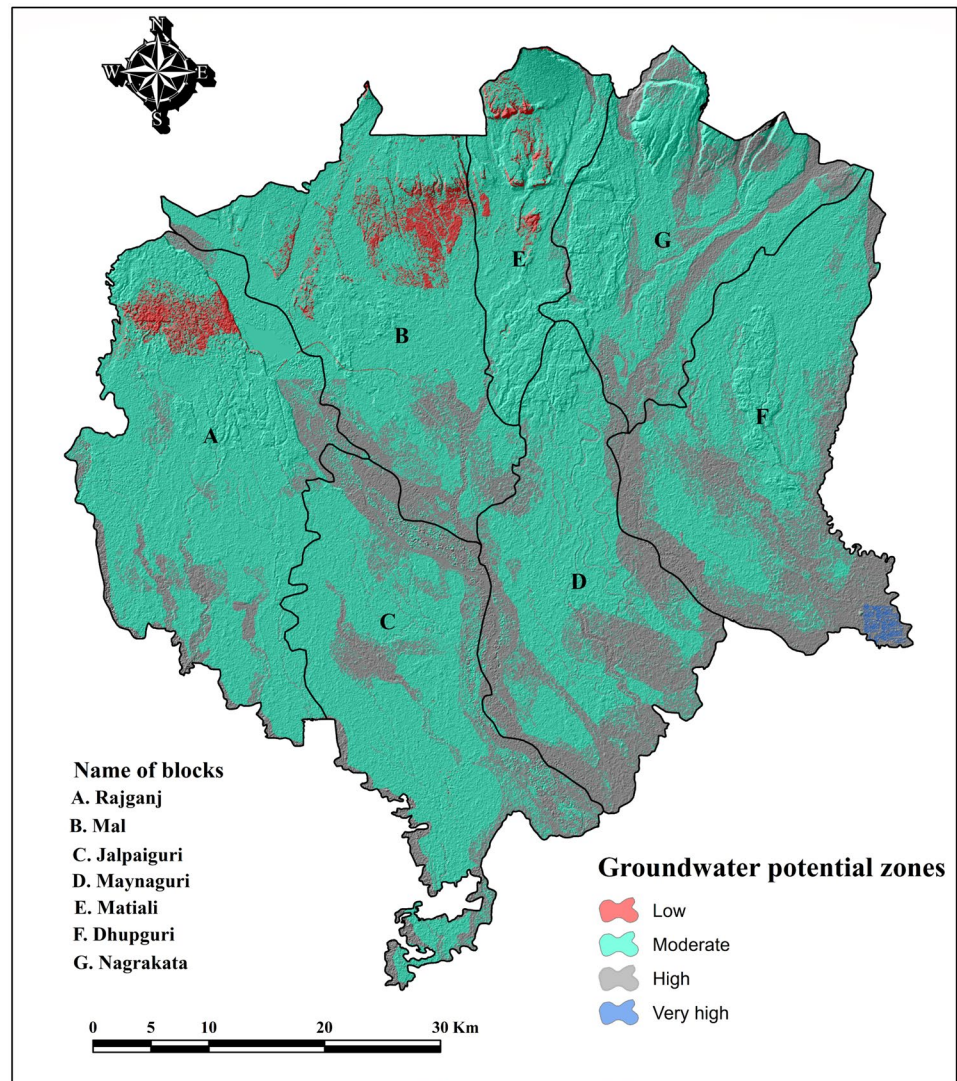


Table 9 Distribution of groundwater potential zones (GPZs) in the Jalpaiguri district

GPZs	Area (in km ²)	Area (in percentage)	Characteristics of the zones	Respective block
Very high	03.20	00.10	Very low elevation, gentle slope, very high intensity of rainfall, very high infiltration capacity, very high groundwater level, younger alluvium plain, maximum groundwater prospects	Dhupguri,
High	813.99	24.05	Low elevation, high intensity of rainfall, younger and piedmont alluvium soil, high groundwater level, high infiltration capacity	Dhupguri, Maynaguri, Nagrakata, Jalpaiguri
Moderate	2472.11	73.00	Concentration of settlements relatively high, moderate to high elevation and drainage density, variety of soils, covered maximum area of the region	Rajganj, Jalpaiguri, Nagrakata, Matiali, Mal, Maynaguri Dhupguri
Low	96.70	02.85	Very high elevation, dense vegetation, low groundwater level, steep slope, high runoff, low annual rainfall, older alluvium, rugged topography, low groundwater prospects	Mal, Rajganj, Matiali

Table 10 Block-wise groundwater potentiality distribution (in percentage)

Block	GPZs			
	Low	Moderate	High	Very high
Rajganj	4.67	84.09	11.24	–
Nagrakata	0.20	71.00	28.80	–
Matiali	6.93	90.51	2.56	–
Maynaguri	0.01	60.00	39.99	–
Mal	8.40	78.10	13.50	–
Jalpaiguri	0.05	72.53	27.42	–
Dhupguri	–	62.66	36.10	1.24

found in the eastern, south-eastern, southern, south-western, and western parts of the block. Parallely, Dhupguri block show ‘high’ GPZ 36.10% area in the north-eastern, eastern, south-eastern, southern, and south-western parts; Nagrakata block show 28.80% area in the northern, north-western, southern, and central parts; Jalpaiguri block show 27.42% area in the northern, north-eastern, eastern, south-eastern, and central parts; Mal block show 13.50% in the southern and south-western parts; Rajganj block show 11.24% area in the northern, eastern and southern parts; and Matiali block shows 2.56% area in the north-eastern and eastern parts. In respect of ‘moderate’ GPZ, the Matiali block represents the highest (90.51%), while Maynaguri shows the lowest

(60%). The block-level groundwater potentiality has been illustrated in Fig. 5. The outcome of the study reflects that moreover the district has good groundwater prospects, and the CGWB (2019) reported that the district falls in the ‘safe’ groundwater zone in the country.

Verification of GPZs

Groundwater table depth has a direct relation with groundwater potentiality. The groundwater depth varies from region to region, and the lower depth of groundwater represents more potentiality than regions with a higher depth of groundwater (Mahato & Pal, 2019; Oikonomidis et al., 2015). Generally, in the sub-Himalayan West Bengal during the pre-monsoonal months (March–May), the groundwater level is far away from the surface whereas, during monsoonal months, the depth considerably becomes very low to the surface (Pal et al., 2020). To show the regional variation and annual changes of the depth of the groundwater, the CGWB (2019) data here is used. In the district, the groundwater level varies from 0 to 10 mbgl in the monsoonal season (August 2019) and 0 to 20 mbgl in the non-monsoonal season (April 2019). The groundwater depth has been manifested in Fig. 6, which reveals a significant fluctuation in the water level from monsoonal to non-monsoonal months.

Parallely, 11 observation wells of CGWB in the Jalpaiguri district were also considered to cross-verification.

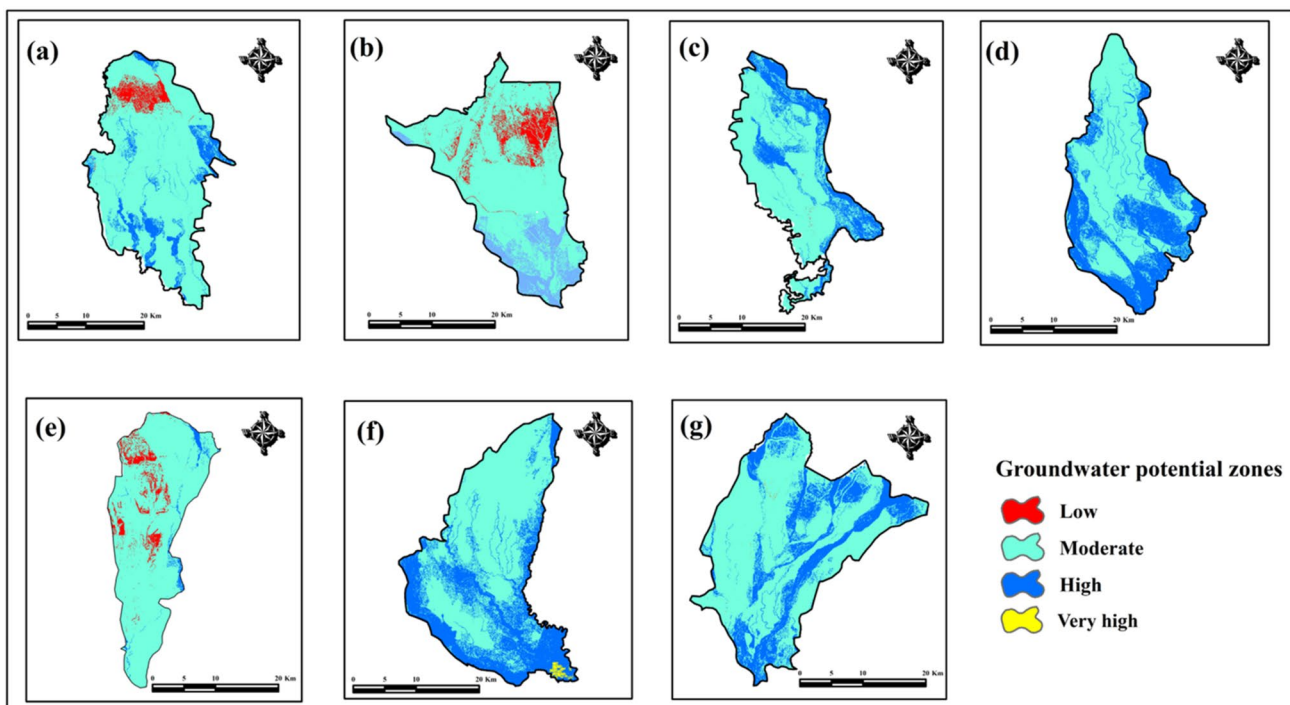


Fig. 5 Groundwater potential zones (GPZs) of a Rajganj, b Mal, c Jalpaiguri, d Maynaguri, e Matiali, f Dhupguri and g Nagrakata block in Jalpaiguri district

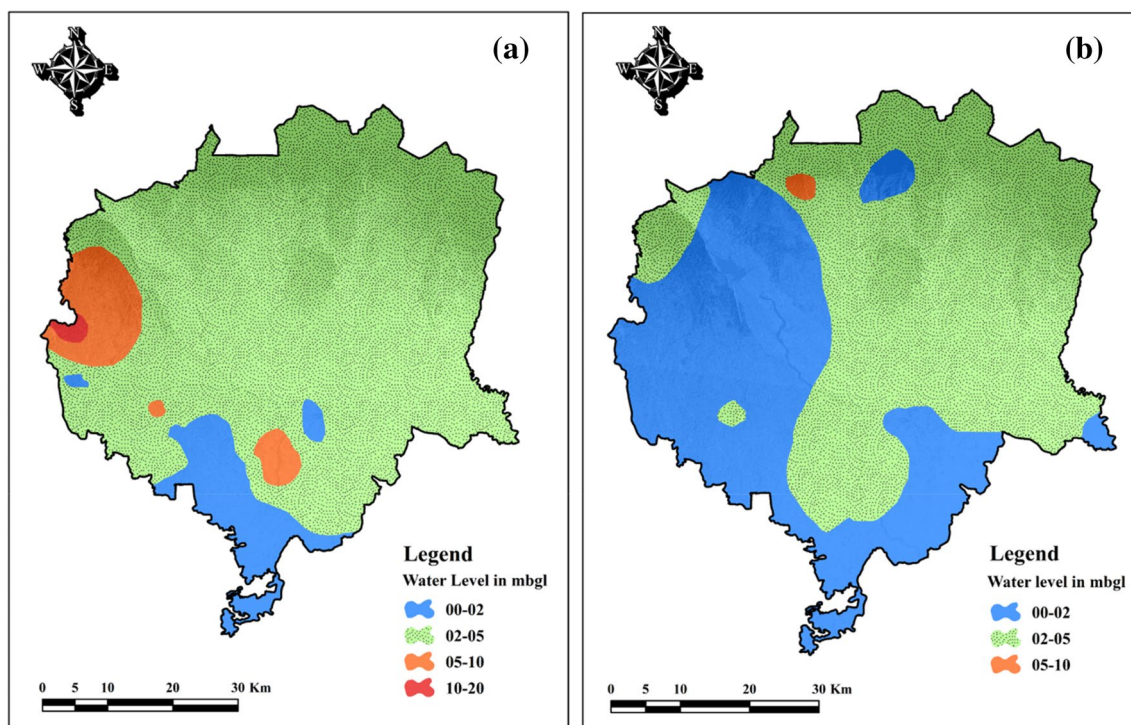


Fig. 6 **a** Pre-monsoonal and **b** monsoonal groundwater level (in mbgl) map of the study area

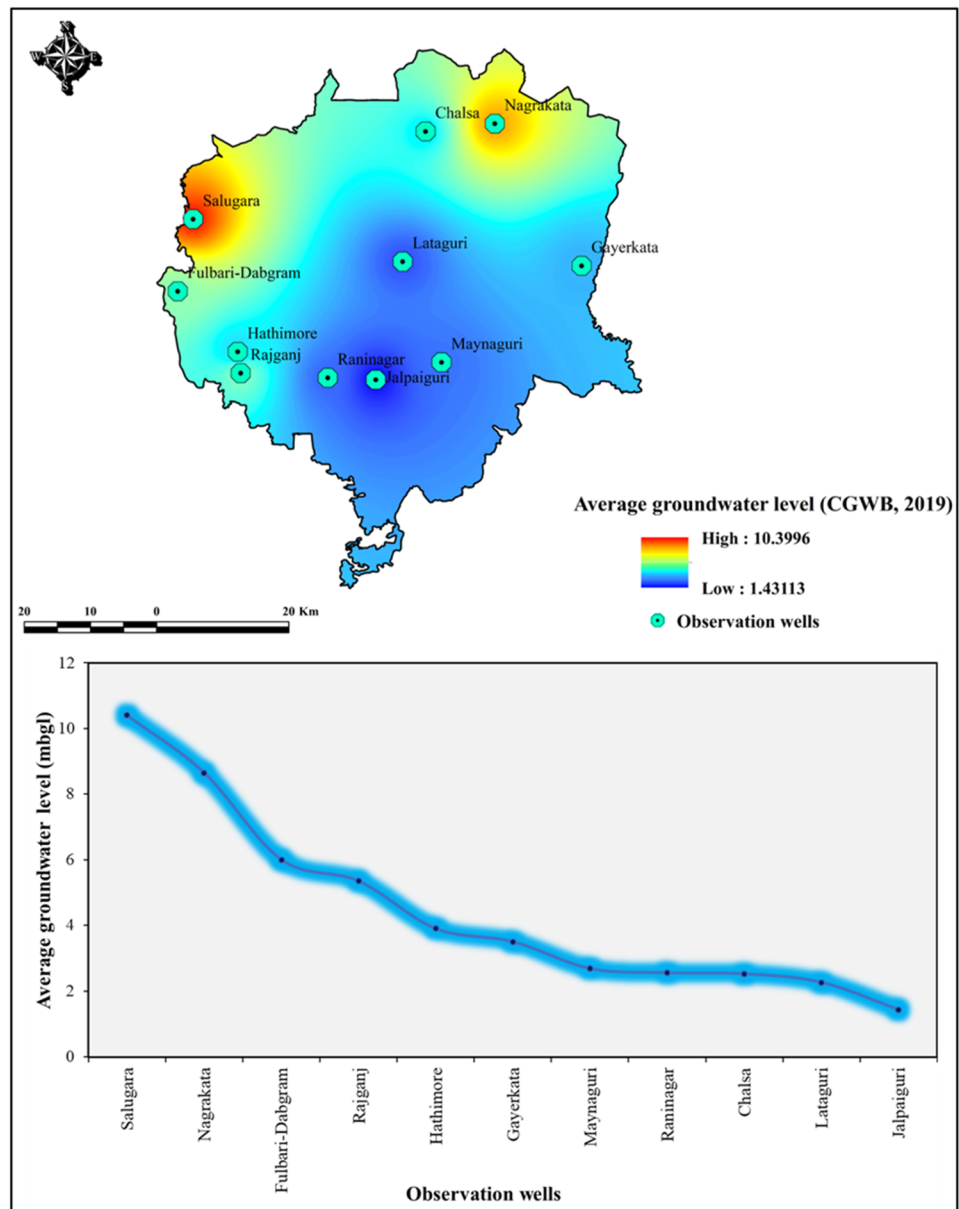
The groundwater level of the observed wells was compared with the final GPZs. A line graph (Fig. 7) was depicted the nature of the overall groundwater recharge condition of the region. The maximum groundwater level was observed in the well at Salugara (9.51 m) near Siliguri, followed by Nagrakata (8.65 m), Fulbari-Dabgram (5.37 m), Rajganj (5.35 m). These areas are located in the ‘low’ GPZ. The groundwater level found low in the Jalpaiguri (1.43 m), Lataguri (2.26 m), Raninagar (2.55 m) areas, which are fall under ‘high’ GPZ.

The ‘ArcSDM’ tool in the ArcGIS platform has been used to study the ROC-AUC of the model. The ROC graph is basically two-dimensional, where the *X*-axis depicts 1-specificity (false positive rate) and the *Y*-axis depicts sensitivity (true positive rate). AUC represents the area under the ROC curve, which aids in calculating how well the employed model has been performed. For this purpose, true negative points and true positive points were selected from the dug well point data. The ROC-AUC assessment manifests that the model successfully developed the GPZs map (Fig. 8). As the obtained AUC value is 0.715, hence the AHP model performs ‘good’ based on the satisfaction scale (Table 11). Thus, it can be summarized that the produced GPZs were validated properly with the actual groundwater level data of the concerned region.

Conclusion

The present study was conducted to assess the GPZs in the sub-Himalayan foothills region specifically, in the Jalpaiguri district, using the RS, GIS, and AHP methods. Among the nine selected thematic layers, ‘GEOM’, ‘AR’, and ‘LD’ play as key influence factors (60%) to produce the final GPZs map. The outcome of the study manifests majority of the area (2472.11 sq. km or 73%) has ‘moderate’ potentiality, while 96.70 sq. km (2.85%) area was identified as ‘low’ potentiality. The final potentiality map was validated with CGWB data to check the actual condition of groundwater recharge in respect of produced groundwater potential zones. The analysis depicted good prediction employing the AHP method as the AUC of the GPZs map was observed 71.50% (0.715). Due to the expansion of Siliguri city in the north-western part of the region, the water demand is increasing tremendously. Hence, it puts pressure on the urban groundwater level, resulting in negative imprints on the environment and society. During the non-monsoonal season, the urban centers, areas with rugged terrain (like Nagrakata, Mal), usually suffers shortages of groundwater. The groundwater level declines in these areas from 2 to 5 mbgl in the monsoonal season to 10–20 mbgl in the non-monsoonal season.

Fig. 7 AHP Model validation of groundwater potential zones (GPZs) through average groundwater level data of different observation wells of CGWB in the study area



The work helps to identify the areas with special needs where the implementation of the groundwater management programs is relevant. The authorities should influence the local-level groundwater management program, particularly in the urban centers, where optimal uses of groundwater are hampered due to extreme anthropogenic activities. For long-term sustainability of the area, the focuses should be on effective management practices, incorporation of different government agencies, NGOs, local administrative

authorities, as well as improvement of the awareness of the local people. The overall assessment will be helpful for the planners, stakeholders, and government agencies for implementing any future planning over this area. Despite its shortcomings, the multi-criteria decision-making (MCDM) approach can be utilized as a strong tool for examining real-world problems in places where data is scarce, notably in countries of the developing world.

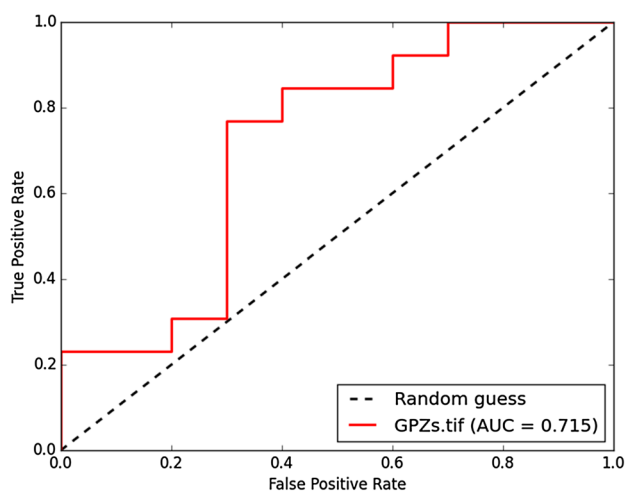


Fig. 8 ROC-AUC assessment of the GPZs

Table 11 AUC range observations along with their descriptions

AUC values	Description
0.50–0.60	Unsatisfactory
0.60–0.70	Satisfactory
0.70–0.80	Good
0.80–0.90	Very good
0.90–1	Excellent

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Declarations

Conflict of interest There are no competing interests declared by the authors.

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