



Extracting of prospective groundwater potential zones using remote sensing data, GIS, and multi-criteria decision-making approach in the Sub-Himalayan Dooars region of West Bengal, India

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Abstract

Groundwater is one of the fundamental sources of fresh water. Currently, the unequal distribution of groundwater poses a significant environmental crisis, leading to scarcity in certain regions and affecting the livelihood of living organisms worldwide. The present study introduces the Sub-Himalayan foothills Dooars, a highly populated and agriculturally based area. To delineate the groundwater potentiality eight different effective parameters have been employed such as slope, geomorphology, soil, LULC, lineament, rainfall, hydrogeology, and drainage density. For the process and development of these eight thematic layers, geographic information systems and satellite images (Landsat 8) have been used to give the normalized weight and rank value in each thematic layer and their sub-criteria. MCDA-AHP-based model is used for overlay analysis to delineate groundwater potentiality (GWPZ). After overlay analysis in ArcGIS 10.2.2 final groundwater potentiality map is further grouped into four potentiality zones, i.e., very high, high, moderate, and low potential zones. A very high potential zone encompasses 22.45 sq. km. in the southern portion of the selected study region. The high potential zone encompasses 1613.32 sq. km in the southeastern part, the moderate zone is covered by 1063.84 sq.km, and the 71.03 sq.km (2.56% area of the region) area is covered by the low potential zone. The available well data from CGWB have been utilized to assess the potential of groundwater in the district, ensuring originality and authentic validation. It is found that there is a correlation between the observed potentiality zone and existing well data. With the growing population in the Sub-Himalayan Dooars region, there has been a corresponding rise in the demand for water. Hence, this research would assist the authorities and policymakers in effectively managing the groundwater resources in the district.

Keywords Sub-Himalayan Dooars region · MCDA · AHP · Water · CGWB · GWPZ

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Introduction

Sub-surface water or groundwater holds immense global significance as a fundamental source of natural water for dwellers, catering to their domestic, industrial, agricultural, and energy production needs (Pradhan 2009; Manap et al. 2012; Neshat et al. 2013; Abdo et al. 2023), and for tourism development (Rani et al. 2018). It also known as subsurface water pertains to the collection of water that is located beneath the surface of the Earth (Bear and Verrijt 1987). It is also a vital element of the water cycle, providing base flow to rivers, wetlands, and other surface water bodies. Groundwater is an essential natural component for plausible economic growth and sustainable development for both industrial and agrarian environments (Agarwal and Garg 2016). Recently, the supply of groundwater resources has been threatened by overexploitation and unsustainable management practices (Anusha et al. 2022a, b). Due to the increasing industrialization and urbanization, the scarcity of groundwater has been progressively worsening every year, as a result of recurring droughts, overpopulation, irrigation expansion, and the pace of industrialization and urbanization (Kumar 2022). The amalgamation of impetuous population growth and the rising water needs across various sectors including municipalities, agriculture, industries, and tourism has also emerged as a significant factor contributing to the depletion of this resource (Australia 2012). The availability of surface water cannot be guaranteed throughout all seasons, particularly during the summer when inadequate rainfall hinders its ability to meet the demand for various purposes. Consequently, groundwater serves as the sole alternative resource to fulfill these requirements (Manasa et al. 2014). Tropical and subtropical regions characterized by high density of population and limited economic development encounter notable obstacles concerning groundwater resources. These areas experience severe issues associated with groundwater resources. India is a vast country with a monsoonal tropical climate, where the rainfall is unevenly distributed and varies seasonally; therefore the availability of surface water is not adequate to fulfill different needs. Hence people depend more on groundwater resources. Therefore, it is crucial to gain a comprehensive understanding of global, regional, and local approaches, solutions, and techniques for replenishing groundwater, managing it effectively, and increasing groundwater levels (Muniraj et al. 2019).

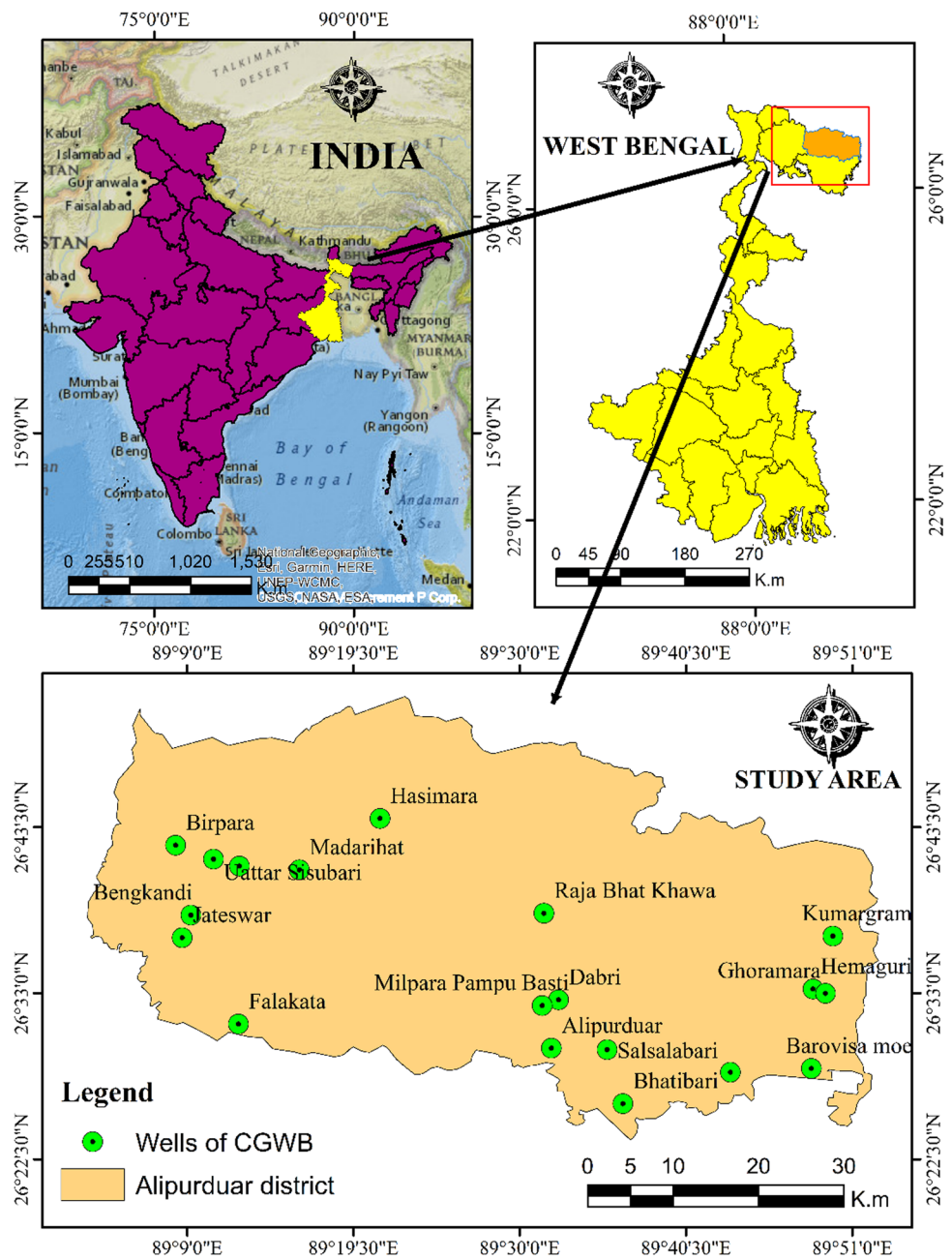
As per the report of CWMI, India is currently facing the most severe water crisis in its history, with approximately 600 million individuals encountering high to extreme water stress. The report also highlights India's low ranking of 120th out of 122 countries in terms of the water

quality index, indicating that around 70% of its water is polluted or contaminated (NITI Ayog 2018). The mean annual rainfall of India is considered sufficient, but certain regions experience an unequal distribution of rainfall, resulting in insufficient replenishment of groundwater and causing water scarcity in those particular areas (Garg and Hassan 2007). In India, more than 90% of the rural population and around 30% of the urban population depend on groundwater as a source of drinking water and household requirements (Reddy et al. 1996). Regrettably, water scarcity and the excessive utilization of groundwater are prevalent in various regions of India (Garg and Hassan 2007; Rodell et al. 2009; Tiwari et al. 1996). As per a report from the World Bank, India is projected to enter into the water stress zone by 2025 and further escalate to the water-scarce zone by 2050.

Recently the increasing utilization of GIS (Geographic Information System) and geo-spatial tools has proven highly effective in managing and monitoring diverse natural resources (Dar et al. 2010; Magesh et al. 2011a, b; Krishna Kumar et al. 2015; Altafi Dadgar et al. 2017; Pasham et al. 2022). Geospatial techniques have also been utilized as crucial tools in assessing and enhancing groundwater conservation and management. Geospatial technology has proven to be a useful method for delineating and modeling potential groundwater zones. The utilization of traditional maps in conjunction with satellite imagery and ground-corrected data has facilitated the evaluation of the potentiality of groundwater and the acquisition of initial information, making this process more accessible. Consequently, numerous studies have employed remote sensing (RS) and geographic information system (GIS) techniques to identify potential groundwater zones, yielding favorable results (Tiwari and Rai 1996; Das et al. 1997; Martz and Garbrecht 1999; Harinarayana et al. 2000; Muralidhar et al. 2000; Chowdhury et al. 2010; Suganthi et al. 2013; Altafi Dadgar et al. 2017). Several scholars have conducted assessments of GWP mapping through the utilization of techniques based on indices (Madrucci et al. 2008; Moges et al. 2019; Datta et al. 2020). In this study, the mapping of GWPZ was conducted for the Alipurduar district in the sub-Himalayan Dooars region of West Bengal, India. The process involved integrating various thematic maps, including land use, geomorphology, rainfall, soil, slope, lineament, drainage, and hydrogeological maps, within a GIS environment to analyze the spatial distribution of GWPZ.

The Analytic Hierarchy Process (AHP), originally developed by Professor Thomas L. Saaty during the 1970s, is a commonly employed method for making decisions based on multiple criteria in different fields (Saaty 1977; Aggarwal et al. 2009; Bhatnagar and Goyal 2012; Kaliraj et al. 2014; Badapalli et al. 2021). This process allows for the breakdown of a problem into a hierarchy, ensuring that both quantitative

Fig. 1 Location map of the study area



and qualitative points of view are taken into account during the evaluation process. In recent times, several studies have suggested that MCDM methods can provide a necessary framework for transparency, and audibility, offering improved structure, and decision-making accuracy in the management of water resources (e.g., Dunning et al. 2000; Flug et al. 2000; Joubert et al. 2003; Machiwal et al. 2011; Adiat et al. 2012; Mallick et al. 2014; Anusha et al. 2022a, b). The integration of MCDA with RS and GIS techniques has led to the effective implementation of the AHP method in various studies focused on water resource management (Saaty 1980, 1986, 1992). This particular study emphasized

the estimation of GWPZ of the Alipurduar district of the Sub-Himalayan Doars region. A total of eight parameters were chosen to analyze and assess the potential areas for groundwater availability. The study aims to fill the gap in understanding the groundwater potential of this area, which has not been thoroughly investigated previously. Therefore, the current study aims to delineate distinct areas with varying groundwater potential by employing a combined approach of MCDA based on the AHP and GIS.

The outcomes of this research hold significant value for future initiatives aimed at sustainable groundwater management. They provide valuable insights and potential strategies

Table 1 Parameters used for ground water potential zone, their sources, and descriptions

Parameters	Descriptions	Source
Geomorphology	Digitized from vector layer and converted into raster data with 30 m*30 m cell size	Geological Survey of India https://www.gsi.gov.in
Soil	Digital soil map of the world-ESRI shape file	FAO http://www.fao.org
LULC	Landsat 8 OLI/TIRS, 30 m*30 m	USGS https://earthexplorer.usgs.gov
Lineament density	Vector later, 1:1,091,958	Geological Survey of India https://www.gsi.gov.in
Hydrogeology	Digitized and reclassification from vector data	West Bengal Disaster Management and Civil Defense https://wbwridd.gov.in
Rainfall	High-resolution gridded data, 0.5°*0.5°	Climatic Research Unit https://sites.uea.ac.uk/cru
Slope	Derived from ASTER DEM (30 m*30 m) using ArcGIS	USGS https://earthexplorer.usgs.gov
Drainage density	Derived from ASTER DEM (30 m*30 m) using fill, flow accumulation, drainage density command in ArcGIS	USGS https://earthexplorer.usgs.gov

to address water crises effectively. Prior to this study, there has been a dearth of research on identifying potential groundwater resources in the Alipurduar district. Therefore, the purpose of this study was to evaluate the zones with high groundwater potential by incorporating additional factors and utilizing the MCDA method. This approach aimed to offer a thorough comprehension of the spatial distribution of GWPZ within the research area.

Study area

The study area belongs to the Sub-Himalayan Dooars region of India. The district is situated in the northeastern corner of West Bengal. It shares borders with Bhutan to the north and Assam to the east. Its geographical coordinates range from approximately 89°0'0" N to 89°50'0" N latitude and 26°15'0" to 26°50'0" longitude (Fig. 1). The study area is situated within the sub-Himalayan foothills region, known as the Queen of Dooars. Spanning an estimated geographical area of 2770.19 square kilometers, the district has an average elevation of 93 m (305 feet). According to the 2011 census, the district has a total population of 1,501,983, with 6.2% residing in urban areas and 93.8% in rural areas.

In terms of climate, the Alipurduar district experiences its highest rainfall during the summer season due to the monsoonal precipitation, while the winter season receives less rainfall. When compared to other districts in West Bengal, Alipurduar receives a higher amount of rainfall, with an annual average exceeding 3200 mm. The mean annual temperature in the study area ranges from 16 to 27 °C. Geomorphologically, the area is characterized by different types of landforms, with a significant portion covered by alluvial

plains and dissected hills. The Torsa and Kaljani rivers, flowing southward, are two prominent perennial rivers in the region. The northern part of Alipurduar District, where the primary slope increases, exhibits lower groundwater potential and deeper groundwater levels.

Data collection

The present investigation primarily relies on the integration of the RS database and GIS to identify potential zones for groundwater availability (GWPZ) in the district. In order to map the GWPZs, eight essential thematic maps or parameters (including geology, soil, rainfall, slope, drainage density, land use land cover, geomorphology, and lineament density) specific to the Himalayan Dooars region have been taken into account based on the theoretical and regional aspects. These parameters were explained in each of the thematic sections separately in the Results and discussion section. The data for this study have been gathered from various domains and processed using GIS tools to construct the necessary database. Geomorphology and lineament density were derived from the Geological Survey of India; land use land cover, slope, and drainage density maps were prepared using data from the United Nations Geological Survey; soil data were gathered from the Food and Agricultural Organization; rainfall data were collected from the Climatic Research Unit; and hydrogeology data were gathered from the West Bengal Disaster Management and Civil Defense. Further, Table 1 lists all selected data descriptions and their respective sources.

Fig. 2 Methodological flow-chart used for identifying the groundwater potential zones

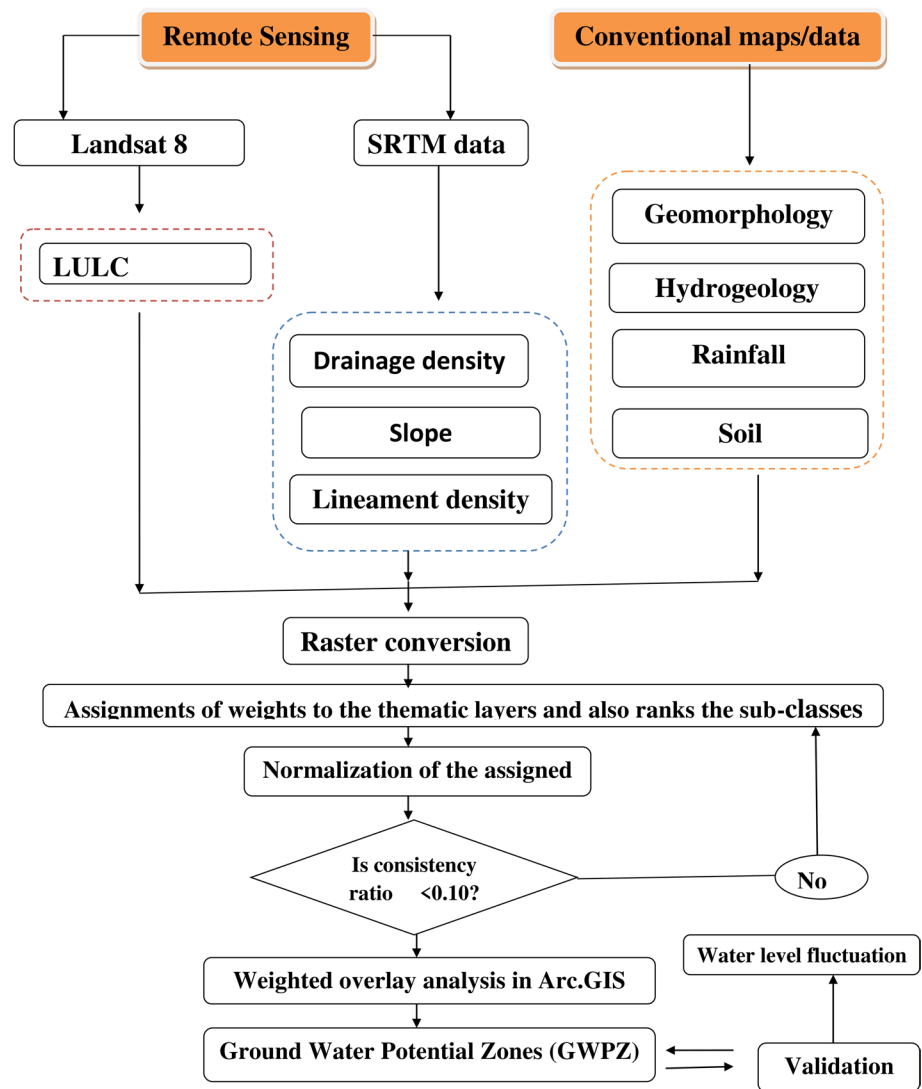


Table 2 Scale of relative importance’s (according to Saaty (1980))

Less important				Equal important	More important			
Extremely	Very strongly	Strongly	Moderately		Moderately	Strongly	Very strongly	Extremely
1/9	1/7	1/5	1/3	1	3	5	7	9

Methodology

The methods used in this investigation include obtaining and creating each of the eight important elements or layers using ArcGIS software. Each thematic factor was geo-rectified and projected to UTM zone 45 north to facilitate easy data processing in the GIS context. The Analytical Hierarchy Process has assigned a weight to the entire geo-referenced

map. AHP was used to determine the weights and rankings that were allocated to each of the eight parameters and their related subclasses, while the database had been generated for all of the categories.

Geology, geomorphology, and lineament density, all of the datasets have been collected as a form of vector layer or format from GSI (Geological Survey of India). After gathering every data in vector format, the GIS environment

converts them into raster layers. Lineament density (LD) was created from the vector data of lineament using density tools in ArcGIS software. Soil information for this study was collected from FAO-DSMW (Digital Soil Map of the World). For the purpose of creating a drainage density and slope map for the present research area, NASA's ASTER DEM has been used. First, DEM data have been processed through the flowing processes of sink-filling, flow accumulation, flow direction, and line density in order to generate drainage density. For creating a rainfall map of the selected area first, rainfall data in gridded form have been collected from Climatic Research Unit (CRU) web satellite data; then, extracting the study area IDW interpolation method was selected. After that, USGS Earth Explorer utilized Landsat 8 OLI (30 m) satellite data for creating the land use land cover (LULC). After gathering the two Landsat satellite images, a single image was created by mosaicking them and then, a LULC map was created using supervised classification.

Subsequently, the MCDA-AHP procedures were applied to complete all the thematic elements and their respective subclasses. The determined weights and rankings were assigned to all parameters and their relevant subclasses. Subsequently, a weighted overlay analysis (WOA) was conducted, leading to the preparation of a GWPZ map for the Alipurduar district. A detailed methodological flowchart is illustrated in Fig. 2.

Multi-criteria decision-making analysis (MCDA) for groundwater potential zone

The most exoteric and widely recognized GIS-based approach for determining potential groundwater areas is through the use of MCDA, which incorporates the Analytical Hierarchical Process (AHP) (Arubalaji et al. 2019; Abdo et al. 2022; Alsafadi et al. 2023). Each groundwater prospecting component or each thematic layer is given a normalized weight using the AHP model (Mitra and Roy 2022; Roy et al. 2022a, b). To streamline the decision-making process,

Table 3 Pairwise AHP comparison matrix of eight thematic layers for groundwater potential zoning

	LULC	DD	LD	Hydrogeology	Rainfall	Slope	Soil	Geom
LULC	1.00	0.33	5.00	0.20	0.33	0.50	0.50	2.00
DD	3.00	1.00	3.00	0.33	0.33	0.25	0.33	3.00
LD	0.20	0.33	1.00	0.14	0.14	0.17	0.33	2.00
Hydrogeology	5.00	3.00	7.00	1.00	0.50	2.00	3.00	3.00
Rainfall	3.00	3.00	7.00	2.00	1.00	2.00	3.00	5.00
Slope	2.00	4.00	6.00	0.50	0.50	1.00	2.00	5.00
Soil	2.00	3.00	3.00	0.33	0.33	0.50	1.00	3.00
Geom	0.50	0.33	0.50	0.33	0.20	0.20	0.33	1.00
sum	16.70	14.99	32.50	4.79	3.33	6.62	10.49	24.00

DD Drainage density, LD Lineament density, Geom. Geomorphology, LULC Land use Land cover

Table 4 Normalized weight matrix of eight thematic layers for groundwater potential zoning

	LULC	Drainage	LD	Hydrogeology	Rainfall	Slope	Soil	Geom	weight
LULC	0.06	0.02	0.15	0.04	0.10	0.08	0.05	0.08	0.07
Drainage	0.18	0.07	0.09	0.07	0.10	0.04	0.03	0.13	0.09
LD	0.01	0.02	0.03	0.03	0.04	0.03	0.03	0.08	0.03
Hydrogeology	0.30	0.20	0.22	0.21	0.15	0.30	0.29	0.13	0.22
Rainfall	0.18	0.20	0.22	0.42	0.30	0.30	0.29	0.21	0.26
Slope	0.12	0.27	0.18	0.10	0.15	0.15	0.19	0.21	0.17
Soil	0.12	0.20	0.09	0.07	0.10	0.08	0.10	0.13	0.11
Geom	0.03	0.02	0.02	0.07	0.06	0.03	0.03	0.04	0.04
sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 5 Scale of relative importance (RI)

N	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

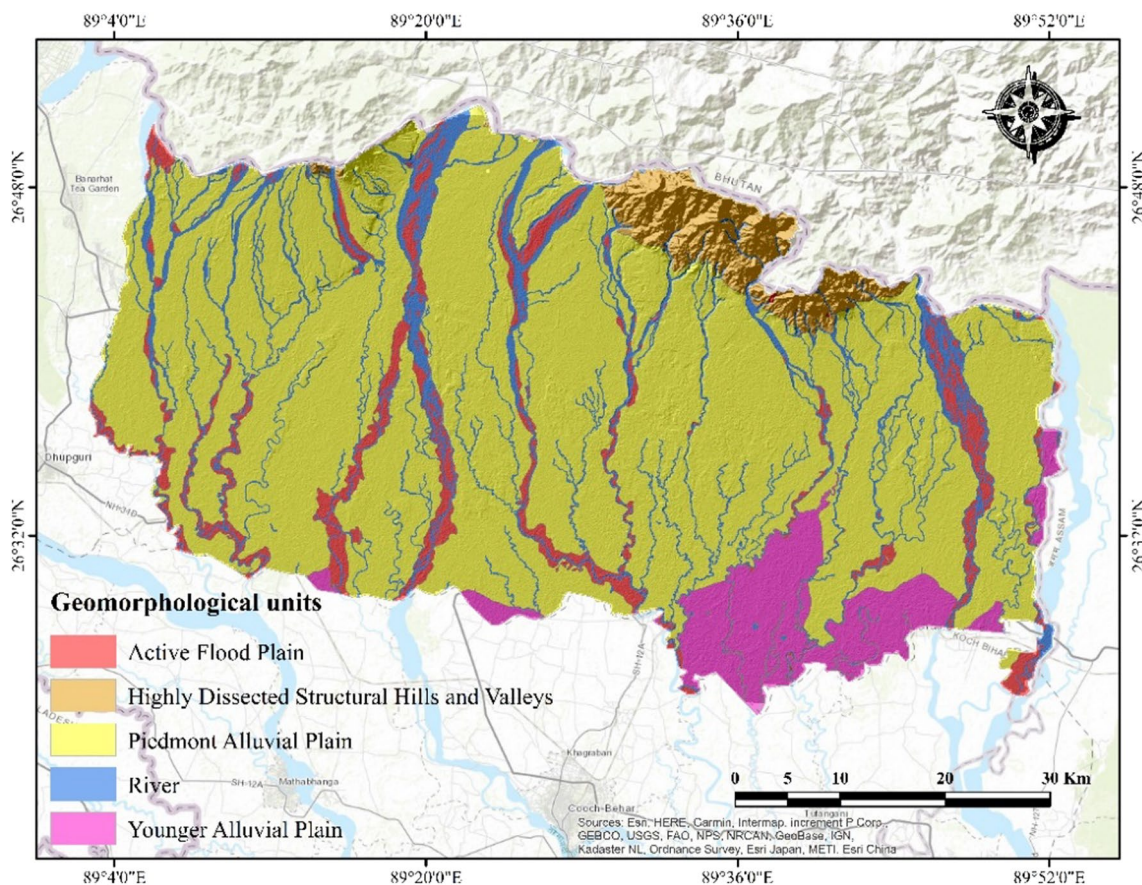


Fig. 3 Geomorphological map of the study area

this approach can be employed by establishing a hierarchical structure with a predefined set of parameters, assigning weights to each criterion (Kiker et al. 2005; Pramanik 2016; Roy et al. 2021). It was first introduced by Saaty (1980). Additionally, there are multiple weight-determining approaches, but AHP is regarded as an attractive approach in groundwater modeling since it may provide fast, dependable, and lucrative effectiveness (Murmu et al. 2019). The weights of each feature have been determined based on their relative significance in the decision-making process for delineating GWPZ (Doke et al. 2021).

The relative relevance of each individual layer is calculated using Saaty's 1–9 scale, where a score of 1 denotes parity between two parameters and a score of 9 denotes extraordinary significance of one parameter over the other (Saaty 1980). The weights for each parameter were established using Saaty's scale of relative importance values, ranging from 1 to 9 (Table 2).

*2, 4, 6, 8 When there is a requirement for compromise, these particular values that fall between the two neighboring judgments are taken into account.

*Reciprocals of the above nonzero important value allotted if activity i has one of the above nonzero numbers

assigned to it when compared with activity j , and then j has the reciprocal value when compared with i .

The comparative matrix primarily consists of reciprocal parameters presented mathematically as $n(n-1)/2$, where 'n' represents the number of variables in the comparison matrix (Saaty 1980; Pramanik 2016).

The AHP was introduced by Saaty and is based on the four very important steps: (Benjmel et al. 2020).

Pairwise comparison matrix

Accurate assessment of relevant information is a critical factor in numerous decision-making techniques (Triantaphyllou and Mann 1995). A strategy determined by pairwise comparisons was suggested by Saaty (1980). A pairwise comparison has been quantified by using a scale. The scale of Saaty is used to determine the outcomes of the pairwise comparisons in the AHP (Saaty 1980). The scale provided includes a range of nonzero values for pairwise comparisons, such as 9, 8, 7, 6, 5, 4, 3, 2, 1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9 (Table 3). These comparisons are utilized to assess the relative importance of each alternative with respect to each criterion, enabling their evaluation accordingly. The

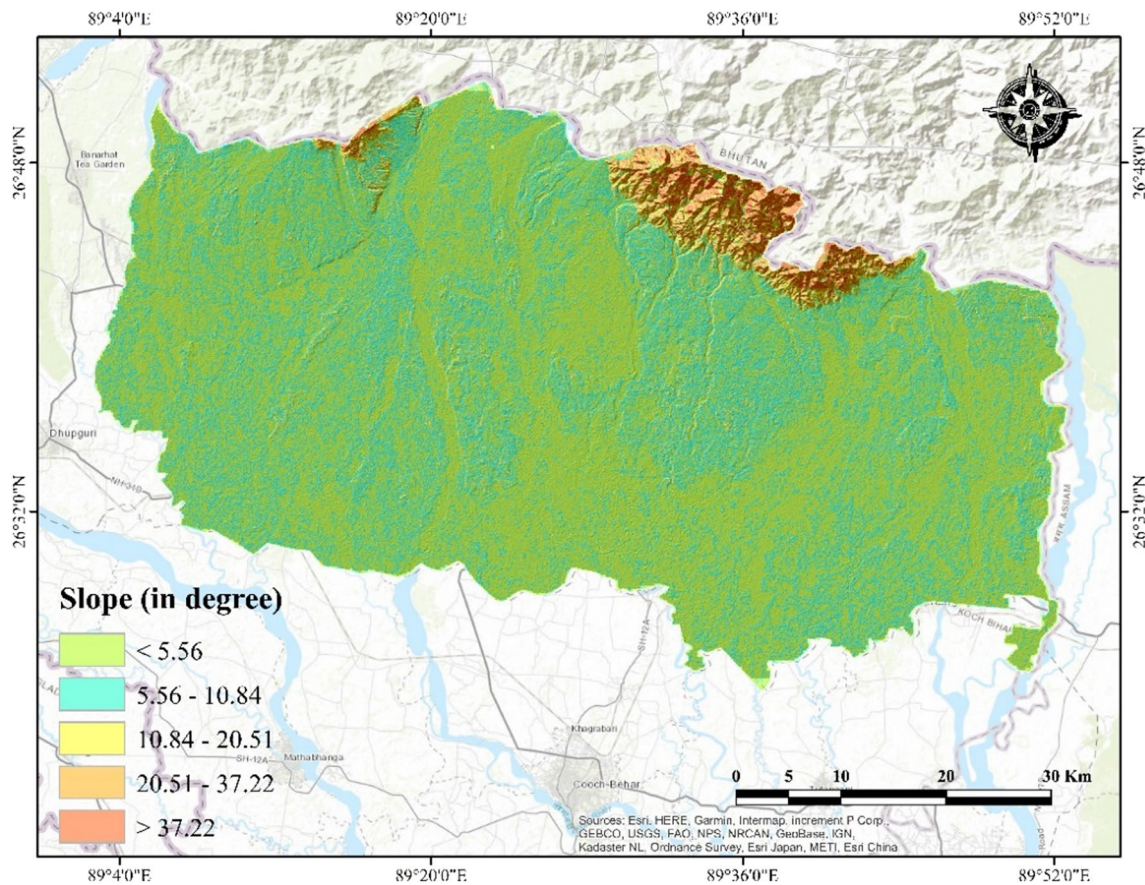


Fig. 4 Slope map of the study area

following formula has been generated for representing the pairwise matrix.

$$AW = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \dots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \dots & a_{nn} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \quad (1)$$

where the pairwise comparison matrix represents AW. An indicator of the pairwise matrix element is referred to as a_{nn} .

Land use has been given importance value 3 in this matrix structure, which indicates that drainage is considerably more essential than land use, which is relatively less significant. As a consequence, the GWPZ has been determined by utilizing the eight parameters matrix method according to their respective relative relevance.

Calculate the normalizing of the weights

To obtain the normalized pairwise comparison matrix, each cell is divided by the total of its respective column. This process results in normalized weights for each factor, which are

determined by calculating the mean of each row, as shown in Table 4.

In Table 3 normalized weight matrixes of eight thematic factors have been shown for groundwater potential zoning.

Consistency index (CI)

The CI formula of Saaty is given below

$$CI = \frac{(\lambda_{max} - n)}{n - 1} \quad (2)$$

In this study, the value of λ_{max} , which represents the principal eigen value of the matrix, was calculated as 8.69. Additionally, the number of factors taken into account for assessing groundwater potential, denoted as "n," is 8. Consequently, the consistency index (CI) value is determined to be 0.098. It is essential to compute the consistency ratio by utilizing the CI value (Table 5).

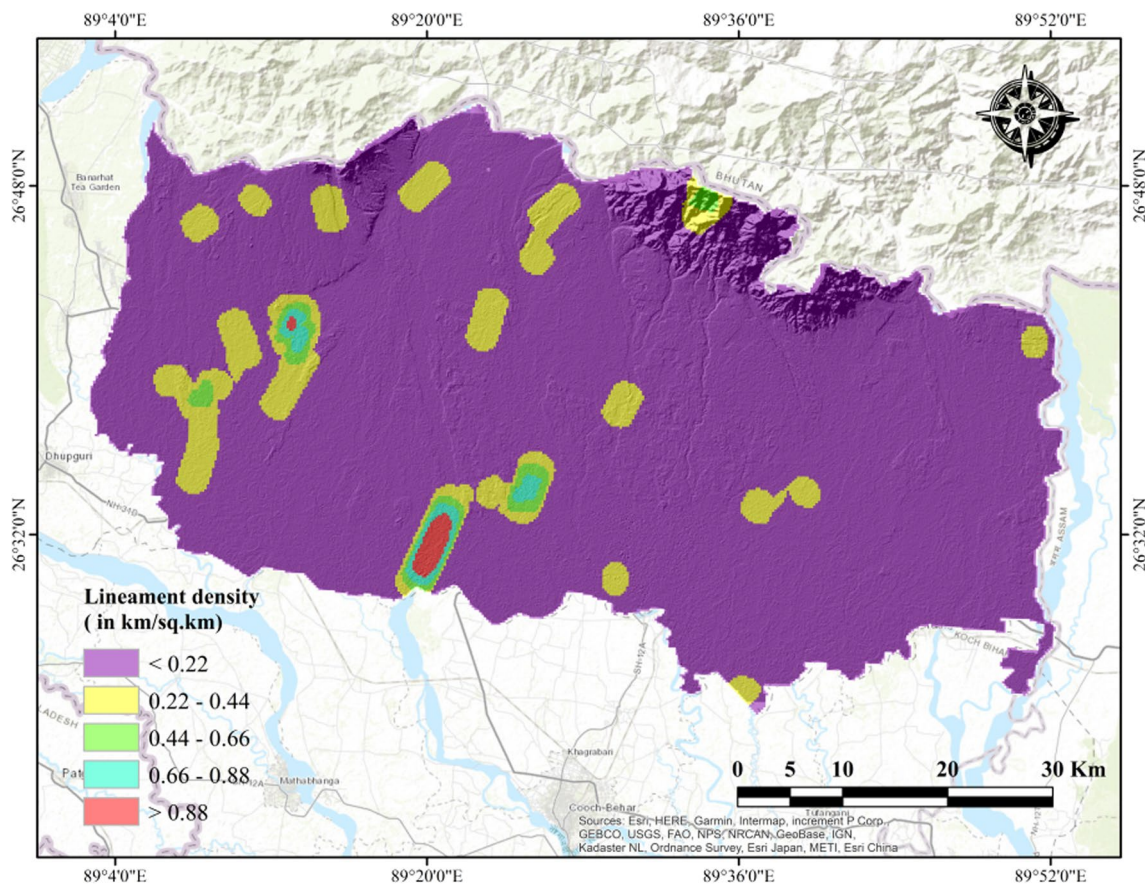


Fig. 5 Lineament density map of the study area

Consistency ratio (CR)

The CR formula for Saaty's AHP approach is

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

where the CR is computed by dividing the CI by the RCI proposed by Saaty. In order to maintain consistency in judgments, the CR value should be less than 0.1. In this case, the calculated consistency ratio (RC) is 0.06, indicating a high level of consistency. Thus, the entire judgment based on the 64 significant pairwise matrices is deemed valid for assessing the groundwater potentiality of the Alipurduar district.

Weighed overlay analysis (WOA)

The ‘WOA’ is a valuable technique that integrates and evaluates input components using a standardized scale of values. It utilizes the pairwise comparison matrix obtained from the AHP to determine the relative importance of these components (ESRI 2015).

$$WOA = \sum_{i=1}^n W_i \times R_i \tag{4}$$

Here, W_i represents as a particular decision criterion, R_i refers to the raster layer of that particular factor, and n represents the number of decision matrix.

Delineation of GWPZ

The sub-surface or groundwater potential areas in a particular area have been estimated using the dimensionless numerical approach known as GWPI (Rahmati et al. 2015; Razandi et al. 2015). The weighted overlay analysis tool utilizes the equation presented below to reclassify values in the input raster layers, aligning them with the accepted assessment scale of 1, 2, 3, and 4 representing very high, high, moderate, and low potential, respectively. To accomplish this, the process involves multiplying the cell values of each parameter class by their respective weight factors and then summing the resulting values of the cells. The outcome of this process is a map depicting groundwater potential recharge zones (ESRI 2015; Raviraj et al. 2017; Lentswe and Molwalefhe 2020).

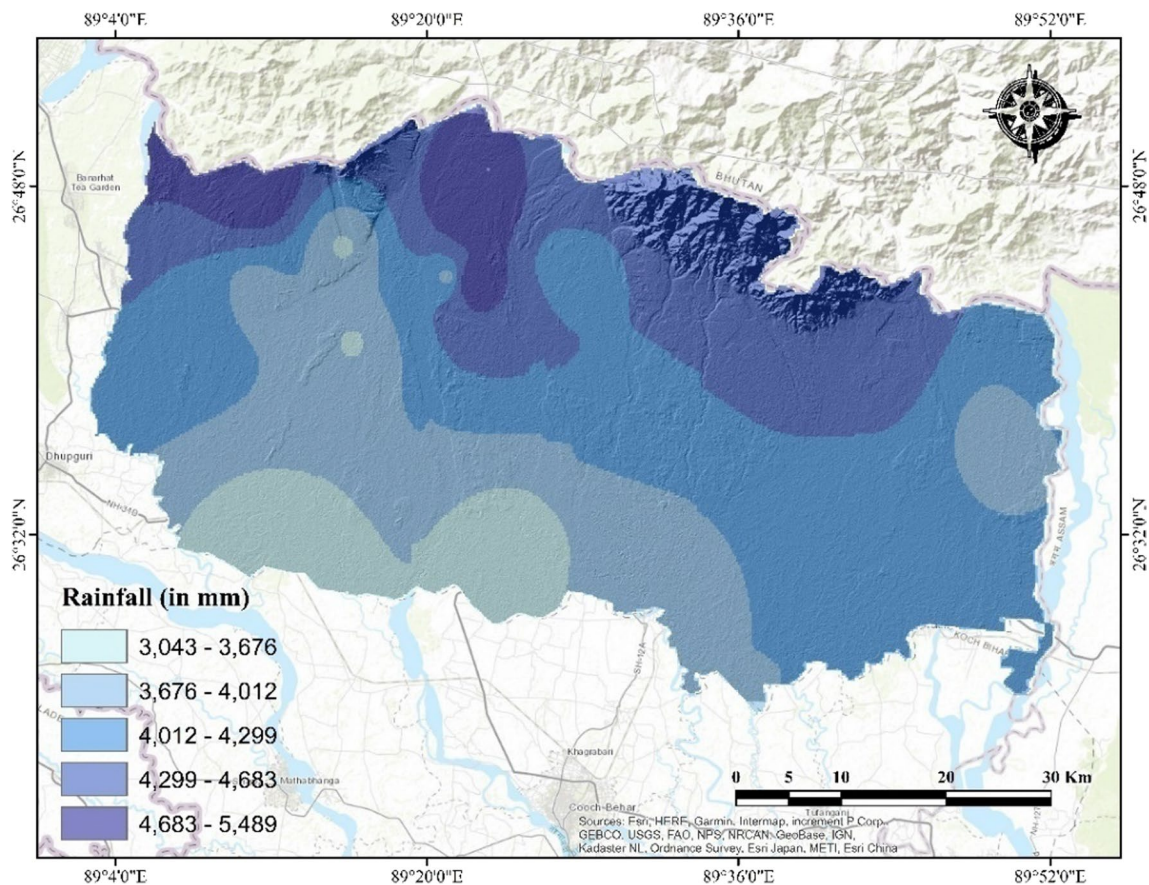


Fig. 6 Rainfall map of the study area

$$\begin{aligned} \text{GWPI} = & \text{GM}_w \text{GM}_r + \text{GE}_w \text{GE}_r + \text{RF}_w \text{RF}_r + \text{DD}_w \text{DD}_r \\ & + \text{SO}_w \text{SO}_r + \text{LULC}_w \text{LULC}_r + \text{SL}_w \text{SL}_r + \text{LI}_w \text{LI}_r \end{aligned} \quad (5)$$

where W = normalized weight of each thematic layer; r = rank of each subclass. GM = Geomorphology; GE = geology; DD = drainage density; SO = soil; LULC = land use land cover; SL = slope; LI = lineament. Based on the above calculations, based on above calculation the entire region has been divided into 4GWP zones, viz. 'low,' 'moderate,' 'high,' and 'very high.'

Results and discussion

Geomorphology

The identification and classification of numerous landforms and their structures as well as water movement, and freeze-thawing are all parts of geomorphological mapping (Arulbalaji et al. 2019). The geomorphology influences the distributional formation of several landforms and their forms. It provides knowledge regarding the geology of a certain

place that is crucial for groundwater research (Machiwal et al. 2011). Geomorphological landforms are the important elements for comprehending groundwater occurrence and its prospective and flow. This work covers a Himalayan foothills region with a variety of geomorphological aspects. Geomorphologically the Alipurduar district is divided into five distinct classes, viz. active flood plain, hills and valleys, several piedmont alluvial plains, different perennial rivers, and younger alluvial plain (Fig. 3). The areal extent of all the geomorphologic elements is that piedmont alluvial plain covers 2041.35 km² which is 72.80% of the study area, followed by active flood plain (212.23 km², 7.50%), younger alluvial plain (202.67 km², 7.24%), river and water body (216.73 km², 7.83%), and dissected hills and valleys (127.90 km², 4.55%). Among all the geomorphological features piedmont alluvial plain dominates the largest percentage of the area which is located throughout the study area except the extreme northern and southeastern portion. Water bodies and active floodplains both are considered the most potential features for groundwater storage because rivers in the Himalayan region carry water in all the sessions. As a result, higher weightage has been given to these features. The dissected hills are situated on the extreme northern

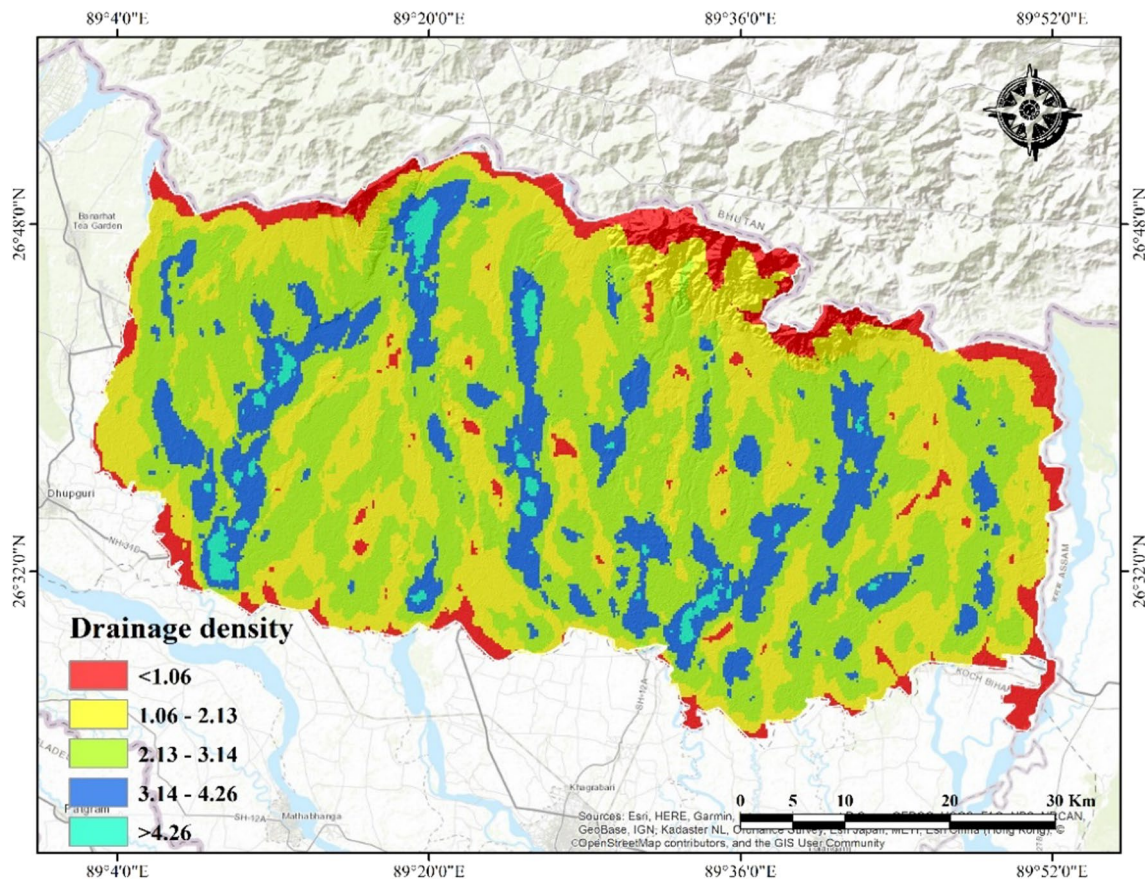


Fig. 7 Drainage density map of the study area

portion of the investigation region where the potentiality of underground water is poor. Hence, lower weightage has been considered for this layer.

Slope

One of the key features of a terrain is its slope, which represents the gradient of the ground surface and provides localized knowledge about geological and geodynamic activities (Thapa et al. 2017). It influences the isolation of precipitation as well as runoff. The slope or gradient of a particular region is always directly proportional to the runoff system, but inversely related to percolation or infiltration rate (Sathathy and Syed 2015). The Sub-Himalayan Dooars region substantially corresponds with the topographically controlled groundwater regions found in previous studies. The selected study area contains higher as well as lower elevations which indicates that the slope is unevenly distributed across the region. As slope and groundwater recharge are inversely proportional to each other, the slope parameter was used for a better understanding of the regional variation of GWP. As Alipurduar district is situated in the foothill region of Bhutan Himalaya, there have been different dissected hills

as well as the plain region. So, in this region the slope ranges from very much less to high such as 2.85° to 30.84° (Fig. 4). For this work, we grouped the slope into five distinct categories, viz. extremely low (< 2.85°), low (2.85°–8.28°), moderate (8.28°–18.28°), high (18.28°–30.84°), and very high sloppy region (> 30.84°). The gentle slopes offer a great chance for groundwater recharging and have promising possibilities for groundwater development because of poor runoff. Hence, the gentle slope class grants a higher ranking. On the other hand, due to insufficient time from the surface to percolate on steeper slopes, the runoff is much higher. Hence, there are maximum chances of less groundwater recharge and lower rank was assigned to the steeper slope class groups. So, based on the weightage of slope classes, it is assumed that the district’s northward side may have very low underground water probability due to maximum slope gradient, while the rest parts may have high to moderate groundwater potential.

Lineament density (LD)

Lineament density is another crucial aspect in examining the GWPZ. Lineament is the existence of joints, faults,

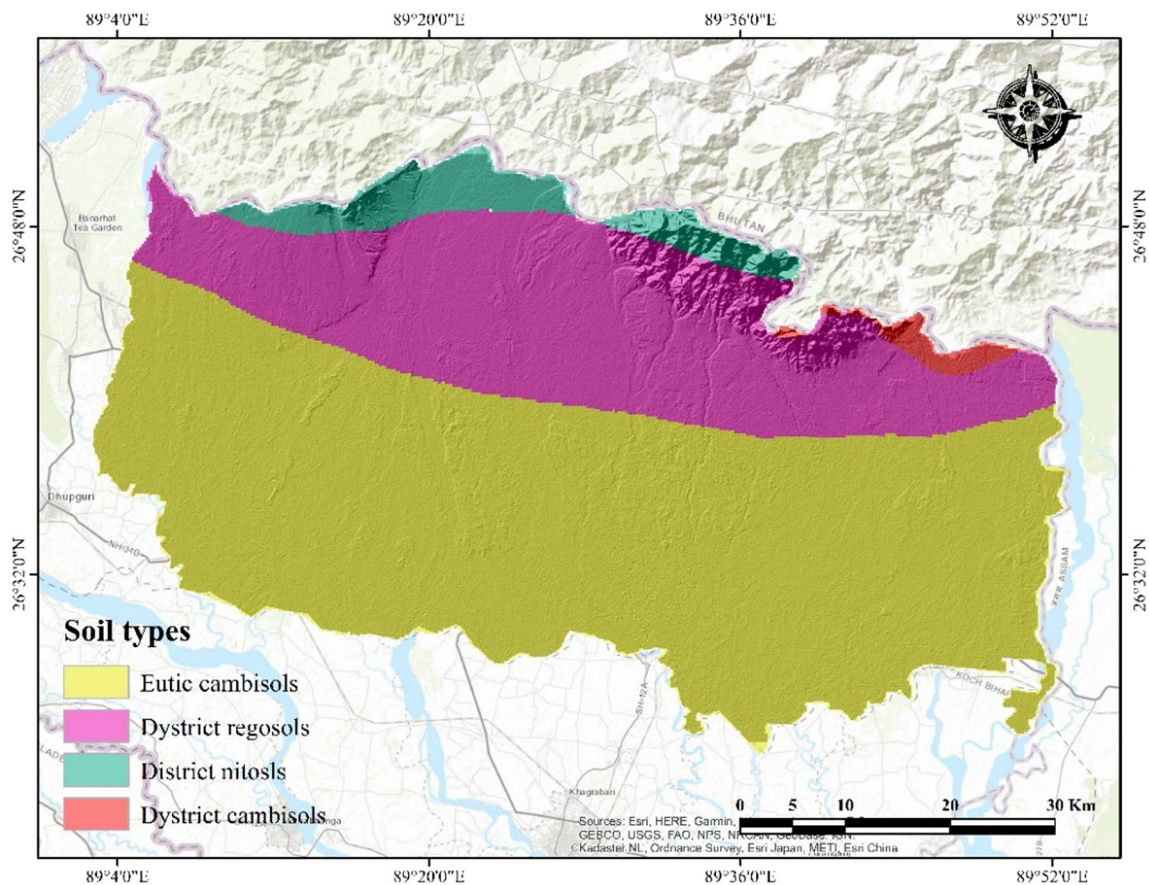


Fig. 8 Soil map of the study area

and fractures that operate as a pathway to drain water into underground storage, and additionally, these can be used as signals of prospective groundwater recharge zones (Pinto et al. 2017). According to Nag and Ghosh (2013), lineament data are easily distinguished from remote sensing data due to their relatively linear alignment and these lineaments are linear or curvilinear in structure. For this work, we used lineament data from the GSI. LD has been studied to determine the orientation and density of fractures and faults in geological formations. The range of LD is 0.22–0.88 km/km² in Alipurduar district. The north and eastward sides have the highest density (0.88 km/km²), which covers only 0.38% of the district's total area (Fig. 5). But it is lowest (<0.22 km/km²) in the north and northeastward portions, which occupies 90.57% area of the district. The presence of Tertiary sediments in these areas may contribute to the higher LD that is associated with groundwater potential. An area with higher LD is related to good GWPZ (Haridas et al. 1998). Henceforth, the higher LD classes are given more weightage.

Rainfall

Precipitation is essential in delineating the source of groundwater in any region. In the case of Alipurduar district, it is the primary hydrological input as the district is the most rainfed district in the state of West Bengal and it has a great influence on groundwater storage in this foothills region. Keeping this theoretical as well as regional aspect in mind, rainfall has been taken as an important thematic layer for the delineation of GWPZ in the district. The annual rainfall data for this work have been gathered from the CRU with a resolution of 0.5° × 0.5°. The rainfall map was prepared using IDW interpolation in ArcGIS. The range of mean annual rainfall is 3043–5489 mm in the study region. For this work, we classified the entire district into five rainfall zones viz. very low (3043–3676 mm), low (3676–4012 mm), moderate (4012–4299 mm), high (4299–4683 mm), and very high (4683–5489 mm) (Fig. 6). Almost 58% of district's total area is covered by very good rainfall zone situated in the north and northwestern portion, whereas 11% area is covered by very low rainfall category located in the southwestern part. However, almost one-third of the study region (31%) is dominated by the medium rainfall category covered horizontally

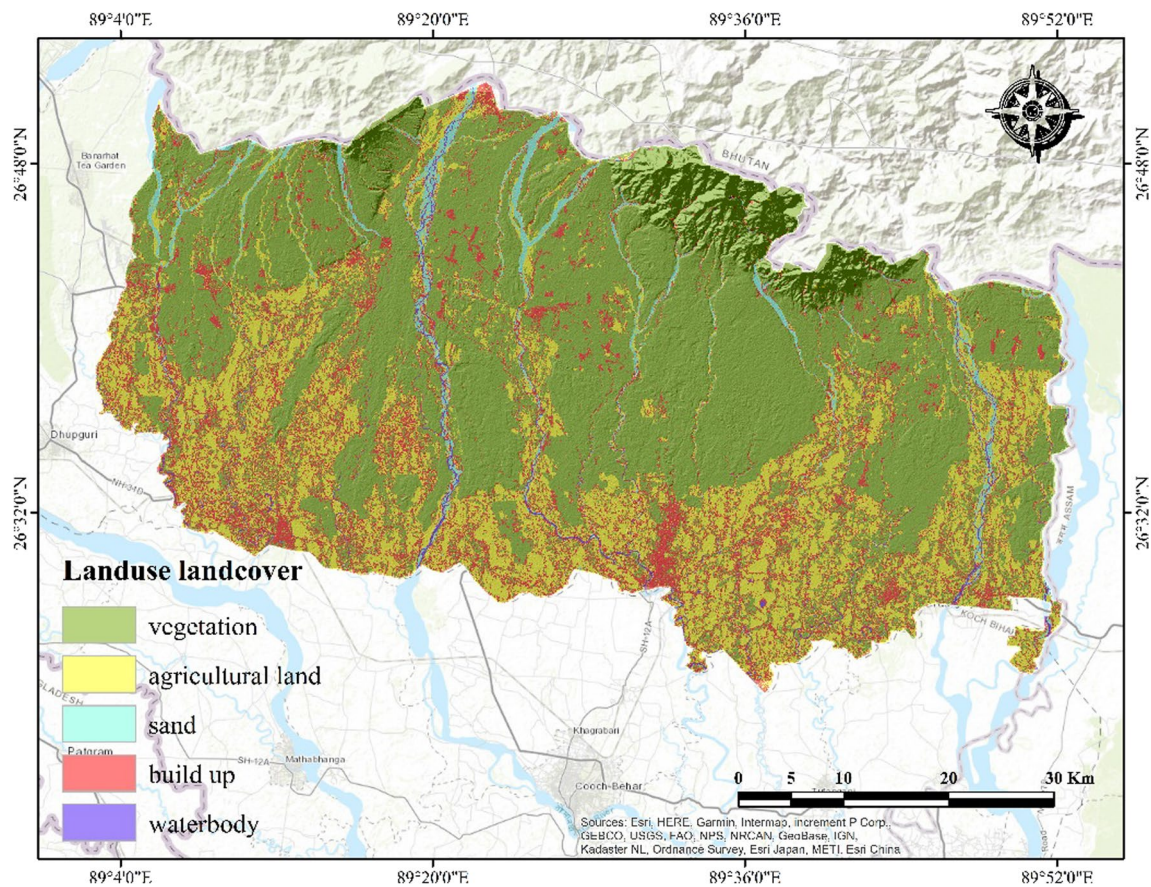


Fig. 9 LULC map of the study area

in the middle portion of the district. The distribution of surface and sub-surface water resources is influenced by rainfall intensity (Wu et al. 2002). In addition, rainfall depth over time has a crucial function in infiltration and groundwater storage. The high-intensity rainfall with short duration has low infiltration and high runoff. On the contrary, the low-intensity rainfall with a lengthy duration possesses a comparatively higher infiltration rate than the surface runoff (Ibrahim-Bathis et al. 2016). Higher rainfall categories were assigned with higher weights.

Drainage density (DD)

The term drainage density relates to stream length per unit area in a watershed (Horton 1932; Strahler 1952). The drainage system is directly related to the groundwater of a certain area. The Dooars region is characterized by a significant number of rivers that originated from the Himalayas and flow in a north-to-south direction. Based on this aspect, drainage density has been taken as a criterion for the present investigation (GWPZ). In this work, we used DEM obtained from NASA for mapping DD. First of all, the

flow direction and accumulation were calculated and then, line density was performed using ArcGIS. DD is influenced by rock structure, soil properties, and slope (Manap et al. 2013; Das et al. 2018). Based on DD (Fig. 7), we divided the entire Alipurduar district into five zones which are very high ($< 1.06 \text{ km/km}^2$), high ($1.06\text{--}2.13 \text{ km/km}^2$), moderate ($2.13\text{--}3.14 \text{ km/km}^2$), low ($3.14\text{--}4.26 \text{ km/km}^2$), and very low ($> 4.26 \text{ km/km}^2$). Both the high and very high zones cover more than one-third (39.43%, i.e., 1108.38 km/km^2) of the district's total area. These zones are examined distortedly in east, middle, and westward parts. Moderate DD class covers a major portion of the district (43.98%, i.e., 1236.28 km/km^2) located subterraneous almost all over of the region. But only 1.61% area (45.26 km/km^2) falls under a very low DD zone situated in the extreme northward and southward portions. DD is inversely related to permeability (Magesh et al. 2012). That means a higher DD is considered to mean more surface runoff and less infiltration rate (Bagyaraj et al. 2013); and the same way, a low DD indicates less surface runoff and more infiltration rate (Arulbalaji et al. 2019). Hence, for groundwater potentiality mapping, the higher ranking was assigned to the lower DD class.

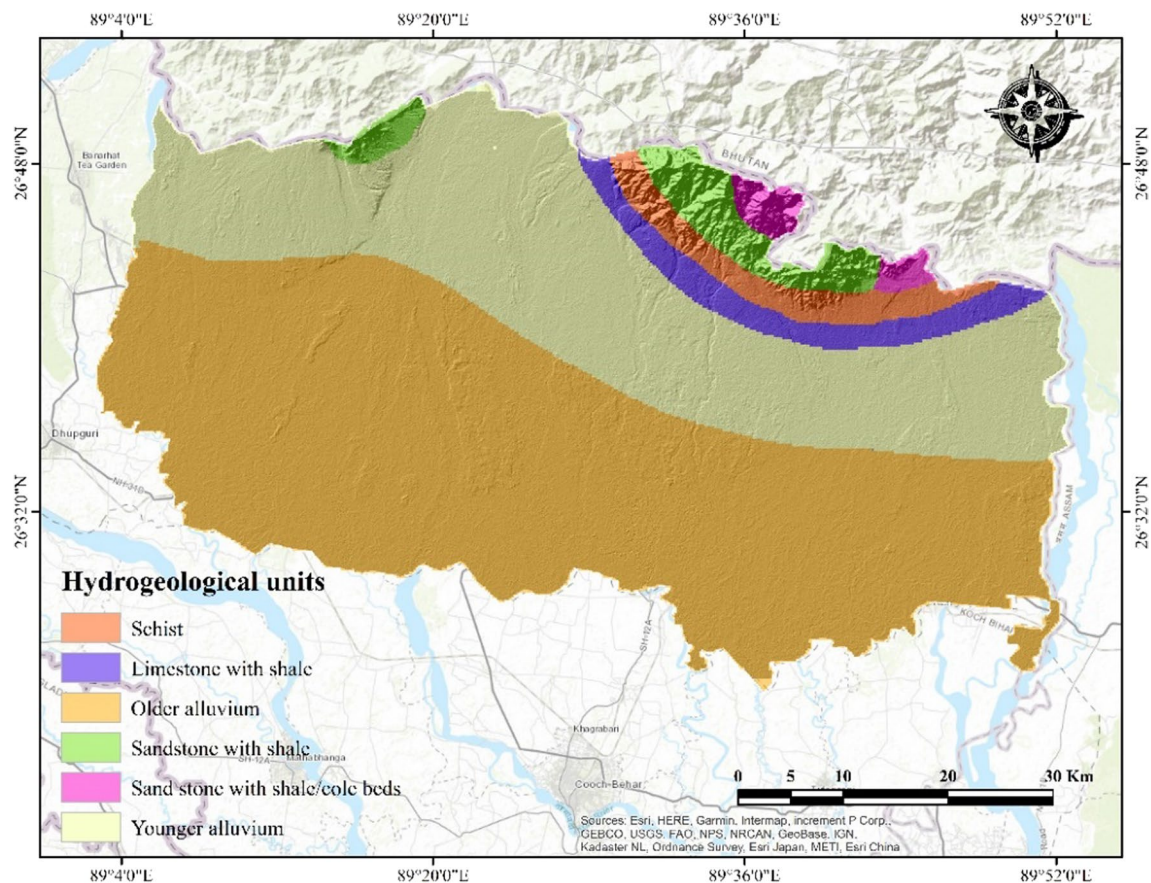


Fig. 10 Hydrogeological map of the study area

Soil

Soil significantly controls the percolation or infiltration capacity as well as groundwater flow or recharge of an area (Saha 2017). The soil serves as a natural filter to remove various impurities from water (Donahue et al. 1983). Land cover items which are significantly associated with water resources prominently depend on the soil types of a region (Sarkar et al. 2023). Therefore, the soil properties and soil types play an important role in the flow as well as recharge of groundwater. The Sub-Himalayan Dooars region is characterized by a variety of soil. The soil data for the Alipurduar district were collected from the FAO. The district falls under four major soil types which are erotic cambisols, dystric regosols, distric nitosols, and dystric cambisols (Fig. 8). A significant area (1811.41 km²) of the district is dominated by eutric cambisols, which covers 64.44% area and situated horizontally from middle to southern portion of the study region. Only 28.67 km² area (1.02%) belongs to dystric cambisols, which is extended toward the northeast. The other two soil groups, namely dystric regosols and distric nitosols, cover 833.74 km² (29.66%) and 136.90 km² (4.87%) of the study area, respectively. Various climatic, geological, and

physiographic characteristics affect the formation of soil (Arya et al. 2020). The amount of surface water that drains into the underlying aquifer is characterized by soil types (Arivalagan et al. 2014) because infiltration rate depends on soil permeability and ability to hold water (Gupta et al. 2018). In foothills of the Himalayas, many of the rivers go through south and alluvial-type soil is gathered. Here, the eutric cambisols soil has high infiltration and percolation capacity and these characteristics of soil are suitable for groundwater flow or recharge. Therefore, the higher weightage has been given to high infiltration. Similarly, the dystric cambisols soil has gained less weight due to less infiltration capacity.

LULC

LULC is considered an important element in hydro-geological studies as it provides an accurate picture of how much groundwater is needed and used (Wagh et al. 2019). LULC map of Alipurduar district has been produced using Landsat 8 imageries in ArcGIS. LULC of this region gives essential information on major land cover features and also gives to make decisions for the zonation of groundwater

Table 6 Categorization of normalized weight and rank of eight thematic layers for groundwater potentiality zoning

Criteria	Sub-criteria	Level of potentiality	Area in sq.km	Area in percentage	Ranking	Weight	Influence
Hydrogeology	Younger alluvial	Very good	1569.66	55.84	5	0.07	7.29
	Older alluvial	Good	920.60	32.75	4		
	Limestone with shale	Good	103.16	3.67	4		
	Sandstone with shale	moderate	97.54	3.47	3		
	Sandstone with shale/coal beds	Low	84.89	3.02	2		
	Schist	Very low	34.58	1.23	1		
Drainage density	< 1.06	Very good	225.16	8.01	5	0.09	8.76
	1.06 -2.13	Good	883.22	31.42	4		
	2.13–3.14	Moderate	1236.28	43.98	3		
	3.14–4.26	Low	421.09	14.98	2		
	> 4.26	Very low	45.26	1.61	1		
Lineament density	< 0.22	Very low	2545.92	90.57	1	0.03	3.46
	0.22–0.44	Low	211.11	7.51	2		
	0.44–0.66	Moderate	27.83	0.99	3		
	0.66–0.88	Good	16.58	0.59	4		
	> 0.88	Very good	10.68	0.38	5		
Geomorphology	Water bodies	Very good	216.73	7.71	5	0.22	22.34
	Flood plain	Very good	212.23	7.55	5		
	Younger alluvial plain	Good	202.67	7.21	4		
	Piedmont alluvial plain	Moderate	2041.35	72.62	3		
	Dissected hill	low	127.90	4.55	1		
Rainfall	3043–3676	Very low	203.89	7.12	1	0.26	26.37
	3676–4012	Low	375.89	13.12	2		
	4012–4299	Moderate	789.96	27.57	3		
	4299–4683	Good	1125.69	39.29	4		
	4683–5489	very good	369.96	12.91	5		
Slope	< 2.85	Very good	1699.25	60.45	5	0.17	17.20
	2.85–8.28	Good	879.84	31.30	4		
	8.28–18.28	Moderate	118.91	4.23	3		
	18.28–30.84	Low	71.12	2.53	2		
	> 30.84	Very low	42.17	1.50	1		
Soil	Eutric cambisols	good	1811.41	64.44	5	0.11	10.95
	Dystric regosols	Moderate	833.74	29.66	4		
	District nitosols	Low	136.90	4.87	2		
	Dystric cambisols	Very low	28.67	1.02	1		
LULC	Water bodies	Very good	20.24	0.72	5	0.04	3.75
	Sand deposits	Very good	78.43	2.79	5		
	Agriculture land	Good	630.51	22.43	4		
	Vegetation	Moderate	1677.32	59.67	3		
	Settlement	low	404.50	14.39	2		

Table 7 Categories of groundwater potential zone

Sl. no	Category	Area (km ²)	Area (%)
1	Low	71.03	2.56
2	Moderate	1063.84	38.39
3	Very high	1613.32	58.23
4	High	22.45	0.81

potentiality. The study region has experienced significant changes in LULC over time, and it has a significant relation to the surface as well as groundwater resources. The LULC of the Alipurduar district depicts that this area is associated with vegetation, agricultural land, settlement, sand deposits, and water bodies. A major part of the region, almost 60% (1677.32 km²), is occupied by vegetation cover situated throughout the district except for the lower and extreme northern part (Fig. 9). Second largest land use type is agricultural land which covered 630.51 km² (22.43%) area, followed by settlement 404.50 km² (14.39%), and sand deposit 78.43 km² (2.79%), respectively. Only 14.39 km² (0.72%) areas are covered by water bodies in the district. Generally, agricultural land has low

runoff and is also inextricably linked to irrigation, which means there is a high infiltration rate, but in the case of built-up or settlement areas infiltration rate is much less (Thomas et al. 2009). The existence of fallow land suggests less groundwater potentiality, while water bodies are in favor of groundwater recharge (Chowdary et al. 2010). In the case of vegetation area, higher coverage of vegetation means higher evapotranspiration rate, which means reduced possibility of percolation to the underground layers (Pani et al. 2016). Therefore, the higher ranks are associated with agricultural land and water bodies; the lower rank is allocated to settlement areas; and the vegetation area is moderately ranked for delineating the groundwater potentiality in this foothill region.

Hydrogeology

The hydrogeological formation of an area is considered the most significant determinant of groundwater recharge because the runoff process and infiltration rate heavily depend on rock permeability (Yeh et al. 2016; Chaudhary and Kumar 2018). Quaternary alluvium is highly permeable and forms an important source of groundwater for human

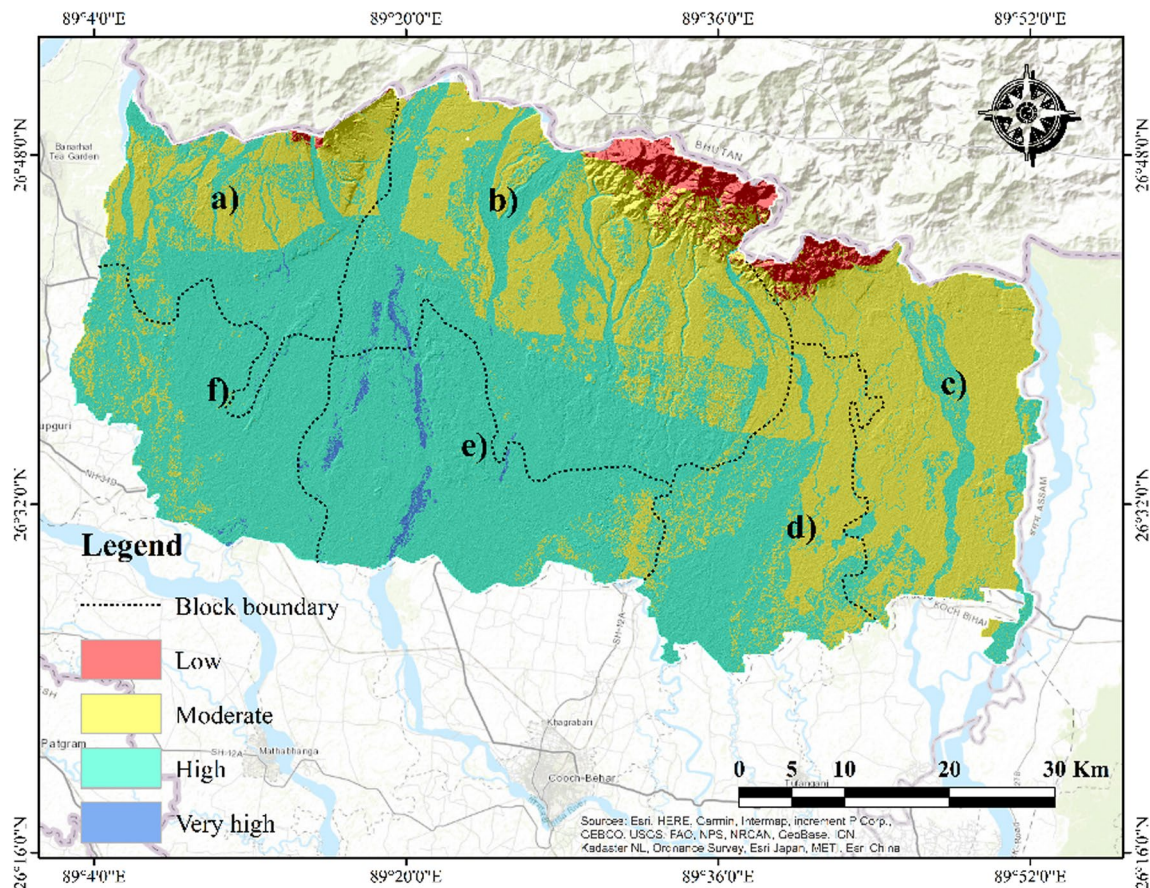
**Fig. 11** Groundwater potential zonation map of the study area

Table 8 Block-wise distribution of GWPZs in Alipurduar district

Block	Class	Area (sq.km)	Area (%)
Falakata	Moderate	8.34	5.78
	High	135.85	94.07
	Very high	0.22	0.16
	Total	144.42	
Alipurduar- I	Moderate	19.07	3.84
	High	461.96	93.05
	Very high	15.45	3.11
	Total	496.48	
Alipurduar-II	Moderate	141.29	37.35
	High	236.98	62.65
	Total	378.27	
Madarihat	Low	1.67	0.46
	Moderate	145.99	40.57
	High	211.19	58.69
	Very high	0.97	0.27
	Total	359.81	
Kumargram	Low	21.59	4.54
	Moderate	354.81	74.64
	High	98.99	20.82
	Total	475.39	
Kalchini	Low	47.77	5.22
	Moderate	394.35	43.06
	High	468.35	51.14
	Very high	5.36	0.58
	Total	915.83	

needs. The Tertiary sediments are less permeable and form confined aquifers. The Precambrian rocks are highly fractured and weathered, and groundwater occurs in fractures, joints, and weathered zones. Many previous studies have covered the hydrogeology of the Alipurduar district. Das et al. (2015) in their research pointed out that the Quaternary alluvium forms are the most significant source of groundwater in the district. They also found that the quality of groundwater is good due to the presence of low total dissolved substances and no evidence of contamination from anthropogenic activities. Another study by Mandal and Chakraborty (2017) found that the Tertiary sediments form confined aquifers with moderate to low yields. They also examined that the Precambrian rocks are highly fractured and the weathering process exists among them. Consequently, groundwater occurs in fractures and weathered zones. The hydrology of Sub-Himalayan Dooars is complex by formation. The presence of multiple geological formations affects the groundwater sources which is further related to water resources. The hydrogeological characteristics of the Alipurduar district vary on the basis of geological formations. According to surveys and field geological investigations, the district is divided into six hydrogeological

subdivisions viz. younger alluvial, older alluvial, sandstone with shale/coal beds, limestone with shale, sandstone with shale, and schist. For this complexity, the hydrogeology criterion has been taken into consideration in decision-making for identifying GWPZs. Major portion (1569.66 km²) of the district is occupied by younger alluvial deposits which is 55.84% areas of district followed by older alluvial (920.60 km², 32.75%), limestone with shale (103.16 km², 3.67%), sandstone with shale (97.54 km², 3.47%), and sandstone with shale/coal beds (84.89 km², 3.02%), respectively. Only 34.58 km² area (1.23%) of the district is covered by schist situated in between sandstone and limestone with shale in the northern portion of the district (Fig. 10). Except extreme northeastern and very few portion in the northern side of the district are cover by younger and older alluvium deposits. The older alluvial rock deposits generally share the same composition as the younger rock deposits, but they tend to be more consolidated and less transmissive. The wealthiest and most widely accessible aquifers are younger alluvium forms as their grain is coarser than that of older alluvium and has substantial hydraulic conductivity. As a result, older alluvium is considered less suitable than younger alluvium for groundwater supply (Chowdhury et al. 2010). Younger alluvium deposits are therefore given higher weights followed by older alluvium deposits and limestone with shale. Sandstone with shale and schist is very much permeable and contributes very little to groundwater storage in the subsurface layer. Hence, lower weightage has been given to these layers.

Ground water potential zone (GWPZ)

The GWPZ of the Alipurduar district in the Sub-Himalayan Dooars has been derived from the GIS platform. The GWPZ has been recognized by employing weighted overlay analysis of selected eight factors, viz. geomorphology, rainfall, LD, hydrogeology, DD, slope, soil, and LULC, using the AHP method in ArcGIS 10.2.2 (Table 6). This research has disclosed that the central and westward portions, notably Madarihat, Hasimara, and Falakata regions in the district, have a very good potential for groundwater, which covered only 0.9% of the study region (Table 7). These parts have several favorable factors, such as loamy soil, high intensified rainfall, the existence of lineaments, flat topography, gradual slope, a huge amount of agricultural land and forest with high infiltration rate, and excellent potential for groundwater recharge. These factors contribute to the very high groundwater potential, making it suitable for agricultural production and groundwater management. Subsequently, the central and SW parts of the Alipurduar district in the Sub-Himalayan Dooars region have high GWPZ, which covers around 63.18% area of the district. The high GWPZ region has suitable factors like flat topography, gentle slope, adequate forest cover area, agricultural

Table 9 Spatial distribution of seasonal variation of ground water level in the study area

Well_ID	Latitude	Longitude	Site Name	Block	Types of Well	Monsoon	Post monsoon	pre monsoon
WBJL57A	26.486	89.503	Birpara	Alipurduar-I	Tube Well	1.01	2.42	2.94
WBJL01	26.616	89.828	Kumargram	Kumargram	Dug Well	2.06	2.23	2.92
WBJL02B	26.725	89.35	Hasimara	Kalchini	Dug Well	2.92	nil	6.3
WBJL03	26.694	89.262	Madarihat	Madarihat	Dug Well	1.68	2.23	2.56
WBJL04	26.514	89.198	Falakata	Falakata	Dug Well	4.34	5.48	5.27
WBJL13	26.85	89.37	Jaigaon	Kalchini	Dug Well	12.47	14.74	22.59
WBJL24	26.4442	89.625	Bhatibari	Alipurduar-II	Dug Well	2.10	3.85	5.31
WBJL25A	26.4717	89.8083	Barovisa More	Kumargram	Dug Well	2.14	3.19	4.2
WBJL26C	26.497	89.524	Alipurduar	Alipurduar-I	Dug Well	2.1	3.44	3.7
WBJL29B	26.615	89.147	Jateswar	Falakata	Dug Well	1.15	2.32	2.33
WBJL37B	26.6911	89.1778	Uttar Shishubari	Madarihat	Dug Well	1.98	3.05	3.09
WBJL38	26.467	89.429	Hghargharia	Alipurduar-I	Dug Well	1.69	3.86	5.18
WBJL39	26.488	89.59	Salsalabari	Alipurduar-II	Dug Well	2.18	3.42	4.36
WBJL47	26.461	89.72	Kamekshaguri, Shantinagar	Kumargram	Dug Well	0.59	2.33	3.56
WBJL48	26.56	89.824	Hemaguri	Kumargram	Dug Well	1.71	2.64	2.52
WBJL49	26.688	89.405	Dabri	Kalchini	Dug Well	1.77	1.8	2.39
WBJL55	26.5375	89.8083	Bara Daldali	Kumargram	Dug Well	Nil	1.77	nil
WBJL56	26.634	89.146	Bengkandi	Falakata	Dug Well	3.97	4.47	4.76
WBJL58	26.609	89.529	MilparaPampuBasti	Kalchini	Dug Well	1.72	2.14	2.27
WBJL73	26.451	89.719	Madhya Kameksha	Kumargram	Dug Well	1.24	2.12	3.16
WBJL74	26.476	89.767	Telipara	Kumargram	Dug Well	1.37	2.88	2.98
WBJL76	26.615	89.53	Raja Bhat Khawa	Kalchini	Dug Well	2.22	2.44	2.6
WBJL78	26.686	89.192	Madhya RagaliBajna	Madarihat	Dug Well	1.30	1.92	3.25
WBJL87	26.548	89.821	Ghoramara	Kumargram	Dug Well	2.49	3.13	3.09
WBJL88	26.534	89.82	Ghoramara	Kumargram	Dug Well	2.16	2.91	2.7
WBJL89A	26.5076	89.8139	Kumargram	Radhanagar	Dug Well	Nil	nil	4.0
WBJL93	26.684	89.216	Madhya RagaliBajna	Madarihat	Dug Well	1.41	1.69	1.71

arable land, new alluvial soil, heavy rainfall, and the presence of a piedmont alluvial zone. In contrast, the northern and northeastern portions of the region had a moderate GWPZ, which covered the district's 33.90% geographical area. In these parts of the district, several unfavorable factors are responsible for moderate GWPZ and among the drivers, low rainfall concentration, low lineament density, and absence of floodplain are more responsible in such cases. The study also identified 3.45% of the district have a low GWPZ mainly in the northern portion of the district, particularly in Lepchakha and Buxa Jayanti hill region. These regions have several unfavorable factors such as higher ground slope, moderate rainfall, presence of limestone and schist, and higher runoff of rainwater and river water. These factors contribute to the low groundwater potential, making it unsuitable for agricultural production and groundwater management. However, Alipurduar district as a whole has several favorable factors like flat topography, gentle slope, and adequate forest cover area, making it suitable for groundwater management with appropriate interventions. The GWPZ map is displayed in Fig. 11.

For better understanding, the GWPZs are also explained in detail at the block level (Fig. 12). The district consists of six blocks, viz. Madarihat-Birpara, Falakata, Kalchini, Kumargram, Alipurduar-I, and Alipurduar-II. The results show that the GWPZs are unevenly distributed across the study region. It is found that three blocks, namely Alipurduar-I, Alipurduar-II, and Falakata blocks, have good potentiality in comparison with the rest (Table 8). In Alipurduar-I, very high, high, and moderate GWPZ covers 3.11% (15.45 sq.km), 93.05% (461.96 sq.km), and 3.84% (19.07 sq.km) area of the block, respectively. In Alipurduar-II, only two GWPZs (high and moderate) cover the entire block. More than two-thirds of the area, i.e., 62.5% (236.98 sq.km), is enclosed by a high zone and 37.36% (141.29 sq.km) falls under the moderate zone. In Falakata, very high, high, and moderate GWPZ covers 0.16% (0.22 sq.km), 94.07% (135.85 sq.km), and 5.78% (8.34 sq.km) area of the block, respectively. All the GWPZs, i.e., low, moderate, high, and very high, are distributed in Kalchini block where the respective figures are 5.22% (47.77 sq.km), 43.06% (394.35 sq.km), 51.14% (0.58 sq.km), respectively. Similarly, in Kumargram,

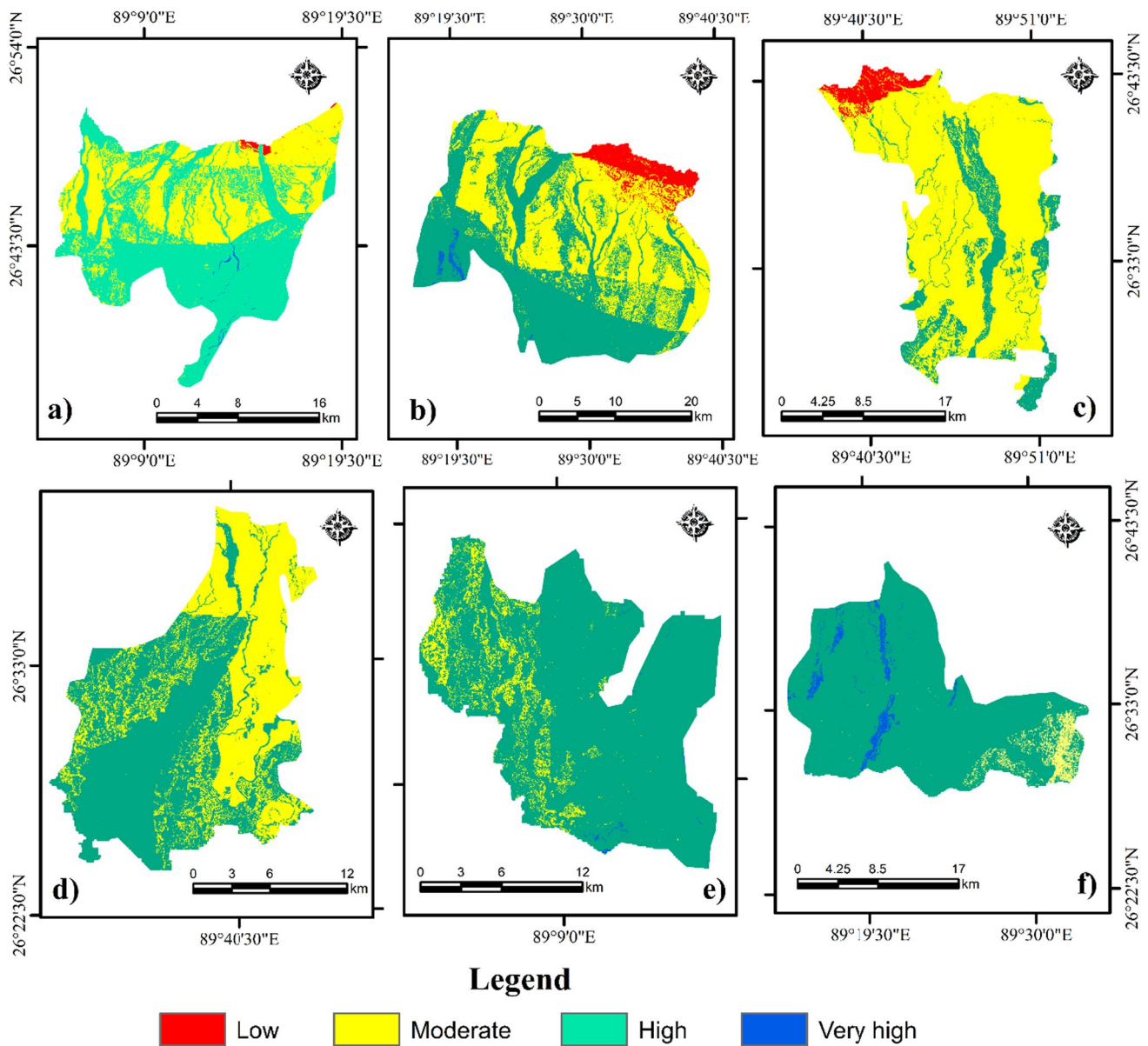


Fig. 12 Seasonal groundwater-level fluctuation mapping, **a** pre-monsoon, **b** monsoon, **c** post-monsoon, **d** mean water level

4.54% (21.59 sq.km) area is covered by low, 74.64% (354.81 sq.km) area is covered by moderate, and 20.82% (98.99 sq.km) area belongs to high GWPZ. In Madarihat, the maximum area falls under high GWPZ comprising an area of 58.69% (211.19 sq.km), whereas moderate is 40.57% (145.99 sq.km), low is 0.46% (1.67 sq.km), and very high is 0.27% (0.97 sq.km).

Validation of the results

The recognized GWPZs in the Alipurduar district were confirmed with the help of the reports provided by the CGWB. The depth of water level in 2022 was investigated in this study, which included 19 wells (Table 9). To determine the groundwater-level fluctuation three seasonal water level maps (before monsoon, monsoon, and after monsoon periods) (Fig. 13) have been furnished in ArcGIS environment using the IDW method. It has been found that well numbers WBJL47, WBJL49, and WBJL03 show very low water levels, these wells were identified to be in a very high potential zone, while the well

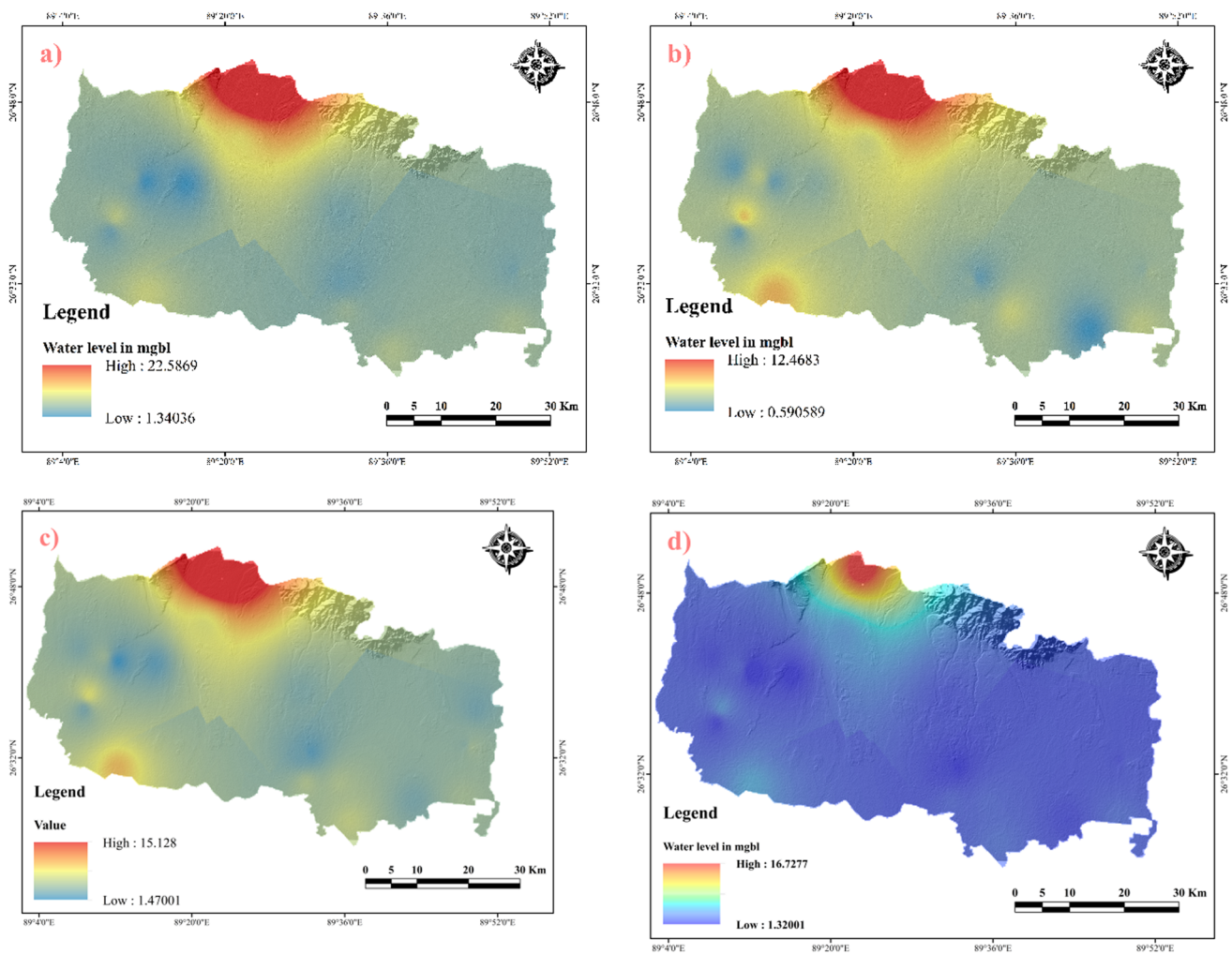


Fig. 13 Block-wise distribution of GWPZs in Alipurduar district, **a** Madarihat, **b** Kalchini, **c** Kumargram, **d** Alipurduar-II, **e** Falakata, **f** Alipurduar-I

numbers WBJL57A indicate low water levels which fall under the high potential zone. Well numbers WBJL25A, WBJL01, and WBJL26C have a moderate type of groundwater level as provided by the CGWD (Fig. 14). In addition, the field survey data also cross-verified the water level of these selected wells in all seasons. For this, the depths of water level were collected from the domestic wells around each selected observation well (CGWD). The district's northern side has low potentiality for groundwater (WBJL13, WBJL04, and WBJL24) because this portion is covered by dissected hills and lithologically this portion also has the rocky type of soil. As a result, this finding suggests that the methodological framework of identification of GWPZ is sound and that accurate findings can be obtained.

Subsequently, the ROC-AUC has been applied to check the reliability of the final GWPZ map. Here, the mean groundwater level (of the observation wells) data provided by the CGWB have been utilized. Generally, the ROC curve can

measure the capability of an affecting element to differentiate two groups. To prepare this curve 19 groundwater well sample data were used. The AUC or ROC value was divided into four classes, viz. poor, moderate, good, and excellent, with ranges of 0.6–0.7, 0.7–0.8, 0.8–0.9, and 0.9–1.0, respectively (Mitra and Roy 2022; Ghosh et al. 2023). In our study, the ROC value is 0.854 which suggests that the ultimate groundwater potential map is precisely authenticated in reality. The ROC curve is illustrated in Fig. 15.

Conclusion

The study of underground water is an important dimension of water resource management in the Sub-Himalayan foothill. The Central Groundwater Board which is the prime agency for managing and protecting water resources in India has been working for a number of decades to develop

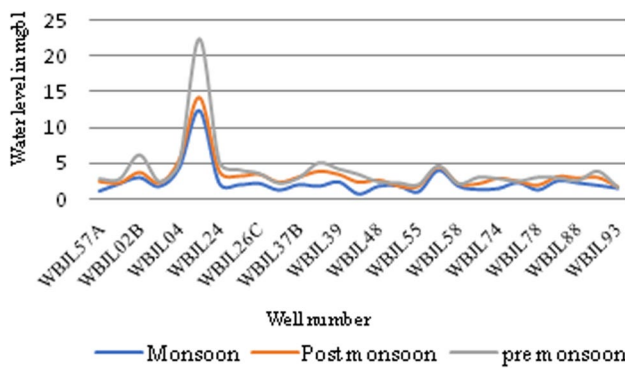


Fig. 14 Well-wise groundwater-level data of Central Ground Water Board (CGWB) in 2021–2022

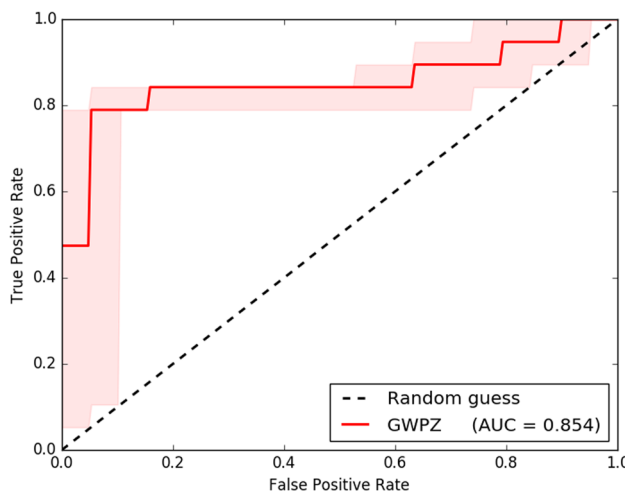


Fig. 15 ROC-AUC assessment for validation with GWPZ

planning and policy that recognize the most suitable locations for the setup of water resources supply points for drinking and irrigation to the predominantly rural as well as urban population. In response to this demand, the current work has created a set of spatial as well as temporal cartographic assistance on the basis of a variety of hydrological, topographic, and geological parameters. Groundwater potentiality in the Alipurduar district was investigated by using spatial-analyzer methods with the help of the MCDM technique. The normalized weight and rank of every element and its sub-classes affecting the groundwater probability in the Sub-Himalayan region were successfully applied using the MCDM–AHP approach. Finally, entire effecting parameters were combined in a single layer and weighted overlay analysis was done as a result GWPZ map was prepared.

The GWPZ map has been categorized into four regions in terms of groundwater potentiality, viz. very good (22 km²), good (1613.32 km²), moderate (1063.84 km²), and

low (71.03 km²). The findings show that geomorphology, rainfall, and hydrogeology are the prime determinants of groundwater potentiality in the study area. Geomorphology and rainfall area considered as the most important influencing factor for groundwater potentials instead of soil and LULC. The entire district falls under a moderate to good type of groundwater potential zone having several perennial rivers from the Himalayas, active floodplains, alluvial plains, and fine loamy to sandy loamy types of soil and high intensified rainfall. In the northern portion of Alipurduar district, groundwater potentiality is low due to the presence of dissected hills and high elevation. If the flow revealed by the reconnaissance investigation is reliable, data validation shows that the forecast information provided by AHP was correct.

In light of the growing populations in the Sub-Himalayan Dooars region, determining the high, medium, and low groundwater potential zones is essential for policymaking and efficiently managing water resources. The groundwater potential zones can contribute to resource allocation and planning. Water extraction and supply might be prioritized in high-potential zone regions. Planning for infrastructure development, such as wells and boreholes, might be concentrated on these areas to optimize water supply. Areas classified as low potential zones might not be appropriate for intensive groundwater extraction. Reducing reliance on groundwater in some locations and investigating other water sources or conservation techniques may be necessary. Adopt sustainable practices to prevent over-extraction and aquifer depletion. To guarantee long-term supply, water quality and levels must be regularly monitored. From this investigation, it is feasible to draw the conclusion that this method is provided as an orientation technique capable of streamlining decisions and suggesting paths for further investigation in relation to hydrogeological exploration.

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Data availability The SRTM DEM (30 m spatial resolution) and Landsat 8 OLI/TIRS (30 m) data used in this manuscript were obtained from the United States Geological Survey (USGS) portal (<https://earthexplorer.usgs.gov>), rainfall data collected from Climatic Research Unit (<https://sites.uea.ac.uk/cru>). Geomorphological and hydrogeological

mapping were framed by obtaining data from the Bhukosh GSI (Geological Survey of India) website (<https://bhukosh.gsi.gov.in/Bhukosh/Public>) and <http://www.wbwridd.gov.in/> website, respectively. The soil data were collected from the FAO of UN (Food and Agriculture Organization) soils portal (<http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faunesco-soil-map-of-the-world/en/>). The data that support the findings of this study are available on request from the corresponding author.

Declarations

Conflict of interest The authors have no conflicts of interest to declare.

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