RESEARCH PAPER

INTEGRATION OF GEOSPATIAL TECHNIQUES AND ANALYTICAL HIERARCHY PROCESS (AHP) IN DEMARCATING GROUNDWATER POTENTIAL ZONES IN LAKHIMPUR DISTRICT, ASSAM, INDIA

Arpana Handique[1], Praduyt Dey[2*], Santanu Kumar Patnaik[2]
[1] Centre for Studies in Geography, Dibrugarh University, Dibrugarh, India
[2] Department of Geography, Rajiv Gandhi University, Itanagar, Arunachal Pradesh, India
***Corresponding author:** praduyt.dey@rgu.ac.in
Received: January 14th 2024 / Accepted: September 1st 2024 / Published: October 1st 2024
https://doi.org/10.24057/2071-9388-2024-3208

ABSTRACT. Overexploitation and climate change have threatened the availability and sustenance of groundwater resources. A proper understanding of the regional distribution of groundwater is crucial to ensure long-term water security. The present study aims to identify the groundwater potential zones in the Lakhimpur district of Assam using the Analytical Hierarchy Process (AHP) in combination with geospatial technologies. The occurrence of groundwater in the region was determined by several factors including geomorphology, lithology, slope, distance from the river, drainage density, lineament density, rainfall, curvature, soil, land use, land cover, Normalized difference vegetation index (NDVI), and topographic wetness index (TWI). These factors organized as thematic layers were utilized to generate a groundwater potential zones (GWPZ) map in the GIS environment. The AHP, an effective decision-making technique, was adopted to assign weights to each thematic layer corresponding to their relative importance in influencing groundwater availability. The GWPZ map prepared using the weighted overlay techniques was categorized into three classes: good, moderate, and poor. The result revealed that the good potential zone comprises 1909.41 km^2 (65.12%), moderate 1018.25 km^2 (34.72%) and the poor zone comprises 4.22 km^2 (0.14%) of the total geographical area. The obtained results of 73.33% (Overall accuracy), 0.708 (ROC-AUC), and 0.50 mbgl (groundwater level fluctuation) between pre-monsoon and post-monsoon prove that the model has performed satisfactorily in identifying groundwater potential zones. The findings provide a framework for the effective exploration and management of groundwater resources, ensuring their future availability in the region.

KEYWORDS: analytical hierarchical process, groundwater potential zone, remote sensing and GIS

CITATION: Handique A., Dey P., Patnaik S. K. (2024). Integration of Geospatial Techniques and Analytical Hierarchy Process (AHP) in demarcating Groundwater Potential Zones in Lakhimpur District, Assam, India. Geography, Environment, Sustainability, 3(17), 109-125
https://doi.org/10.24057/2071-9388-2024-3208

Conflict of interests: The authors reported no potential conflict of interest.

INTRODUCTION

Groundwater is a crucial natural resource that is extensively used for drinking purposes, agriculture, manufacturing, and ecological sustenance throughout the world. According to Das and Pardeshi (2018), "Groundwater is the second largest important freshwater reservoir and the best alternative for human and economic activities in comparison to surface water". The pattern and availability of groundwater in India are very complex due to a wide range of factors that include, diverse geological settings, differential rock types and formations, climatic variations, diverse hydrological characteristics, and variations in land use and land cover practices. These complexities are intensified by the over-exploitation of groundwater resources in several parts of the country, given that more than 90% of the rural population and nearly 30% of the urban population rely directly on groundwater for drinking and other domestic needs (Parthasarathy and Deka 2019). Thus, it becomes essential to identify areas that exhibit significant groundwater potential that address growing water demand and ensure sustainability (Saravanan et al. 2021).

The traditional methods of groundwater assessment that involve geophysical surveys are time-consuming and economically less feasible as they require sophisticated instruments, high-tech manpower, and explicit logistic support (Jha et al. 2010; Manap et al. 2014; Vaddiraju and Talari 2023). Moreover, these survey methods may not always take into account numerous factors that influence the groundwater regime (Oh et al. 2011).

In recent times, remote sensing and GIS techniques have proved to be the most cost-effective, and efficient in identifying potential groundwater locations along with field-based data validation (Chakrabortty et al. 2018; Arabameri et al. 2020). The widely accessible satellite data providing large spatial and temporal information makes it easier to perform groundwater studies (Shekhar and

Pandey 2014). The ability of GIS to manage a huge amount of spatial data has made it a reliable tool for groundwater exploration and management (Abijith et al. 2020; Ahmad et al. 2020; Arulbalaji et al. 2019). Several studies suggest that the integration of multi-criteria decision-making methods with geospatial technology has been excellent in the assessment of groundwater storage and availability (Qadir et al. 2020; Roy et al. 2020).

The Analytical Hierarchy Process (AHP) is considered to be one of the most user-friendly and reliable MCDM methods which are extensively used in a wide range of fields such as regional planning, natural resource management, and environmental monitoring (Agarwal et al. 2013; Adimalla and Taloor 2020; Dar et al. 2020; Dwivedi et al. 2021). The factors influencing groundwater zonation in the study area namely, geomorphology, lithology, slope, distance from the river, drainage density, lineament density, rainfall, curvature, soil, LULC, NDVI, and TWI were selected based on an extensive review of scholarly literature (Table 1). The prime aim of the research is to identify the groundwater potential zone in the Lakhimpur district, located in Assam which will serve as a repository of information that can be used by the decision-makers and policy formulators for effective management of groundwater resources, and maintain sustainability.

MATERIALS AND METHODS

Study Area

The study focuses on the Lakhimpur district of Assam which is located on the northern bank of the Brahmaputra River, comprising a geographical area of about 2277 km^2 and situated between 26^{0}48′ N and 27^{0}53′ N and 93^{0}42′ and 94^0 20′ E longitude (Fig. 1). Its elevation ranges between 56 to 351 meters above sea level. The district is bounded by Arunachal Pradesh to the north, Dhemaji District to the east, Majuli District and the river Brahmaputra to the south, and Biswanath District to the west. The district is well-drained by numerous rivers like Subansiri, Dikrong, Boginadi, and Ranganadi and is known for its fertile alluvial plains and scenic beauty and is relatively flat and is significant for agricultural practices mainly, wet paddy cultivation.

Table 1. Literature review on the control factor selected for the delineation of groundwater potential zone

Authors	Geom	Geol	LD	DD	LULC	SOI	SL	RF	DR	TWI	NDVI	CUR	GWD	Litho
Vaddiraju and Talari 2023		•		•	•	•	•	•	•					
Das et al. 2022	•		•	•	•	•	•	•						•
Hasanuzzaman et al. 2022	•		•	•	•	•	•	•	•	•	•			•
Jari et al. 2022	•	•	•	•			•	•	•					
Mahato et al. 2022	•	•	•	•	•	•	•	•	•	•				
Melese and Belay 2022	•	•	•	•	•	•	•	•		•		•		
Sajil et al. 2022	•		•	•	•	•	•	•					•	•
Deshpande et al. 2021		•	•	•	•	•	•	•			•		•	
Muthu and Sudalaimuthu 2021	•	•	•	•	•	•	•	•						
Saravanan et al. 2021	•	•	•	•	•	•	•	•						

Geom: Geomorphology, Geol: Geology; LD: Lineament Density, DD: Drainage Density, LULC: Land use Landcover, SOI: Soil, SL: Slope, RF: Rainfall, WZT, DR: Distance from the river, TWI: Topographic Wetness Index, NDVI: Normalized Difference Vegetation Index, CUR: Curvature, GWD: Groundwater depth; Litho: Lithology.

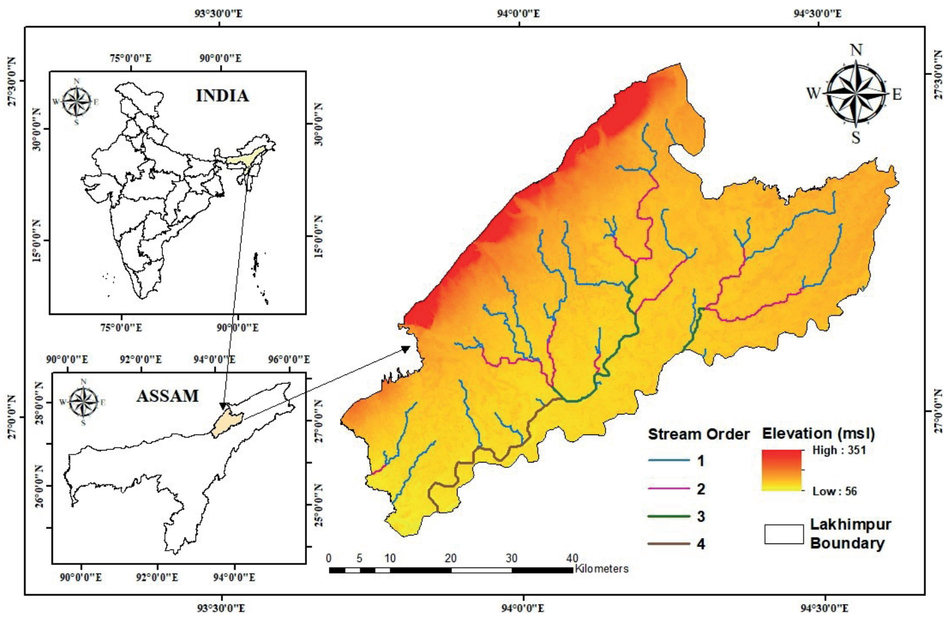

Fig. 1. Location map of the Lakhimpur District, Assam

Thematic layers preparation

The methodological workflow is depicted in Fig 2. The selection of thematic layers for any scientific study is influenced by the geographical location and the researcher's viewpoint (Machiwal et al. 2011). Delineation of the groundwater availability zones is an intricate process that requires careful selection of the causative factors that influence the groundwater regime of any particular region. The research considered thematic layers including geomorphology, lithology, slope, distance from the river, drainage density, lineament density, rainfall, curvature, soil, LULC, NDVI, and TWI which were acquired from different sources (Table 2). The Geomorphology and Lithological unit maps were collected from the Bhukosh, Geological Survey of India for the entire country which was clipped with the study area shape file using ArcGIS software. The Slope, Lineament Density, Drainage Density, Curvature, distance from the river, and TWI were generated using the SRTM Digital Elevation Model at 30 m resolution in ArcGIS using the Arc toolbox functions. The rainfall data was obtained from the Climate Research Unit (CRU) at 5° resolution in grided format for the entire world which was clipped with the study area boundary and was interpolated using the Inverse Distance Weighing interpolation technique in ArcGIS 10.4. The soil map was obtained from the International Soil Reference and Information System (ISRIC) in shape file format and was clipped with the study area accordingly. Land use and Land cover map was generated from the Landsat 8 OLI imagery obtained from USGS Earth Explorer using maximum likelihood classification in ArcGIS. Landsat 8 OLI imagery was also utilized to generate NDVI classes.

Analytical Hierarchy Process and its Application

The Analytical Hierarchy Process (AHP), proposed and popularised by Saaty in the year 1980 was utilized for determining the weights for every thematic layer used in the research (Gautam et al. 2023). AHP is a structural process used in complex decision-making to ascertain the weightage of different factors through a pairwise comparison matrix (Gopinath et al. 2016; Ghosh and Gope 2021). In groundwater and environmental studies, the AHP-based multi-criteria decision-making technique is the most widely recognized and utilized process throughout the world (Shelar et al. 2022).

Weight assignment and normalization

In the process of analysis, the most decisive step is providing weightage to each influencing factor as the outcome is directly dependent on it (Muralitharan and Palanivel 2015). According to Benjmel et al. 2020, "The AHP model has four stages: weight assignment, pairwise comparison matrix, weight normalization, and consistency assessment". To assign a weight, a decision hierarchy was created identifying the importance of different thematic layer and their influence on the groundwater availability of the study area. The pairwise comparison matrix was generated utilizing the causative factors arranged in rows and columns and then ratings were assigned utilizing Saaty's scale which ranges from 1 to 9 (Table 3), where a rating of 1 indicates equal importance and a rating of 9 indicates extreme importance of one criterion over the other (Table 4). Following that the normalized factor weights were derived by normalizing the value of its eigenvector (Table 5). This normalization process is essential to minimize the biases that exist in the weight assignment of the thematic layers (Saravanan et al. 2021). Subsequently, the criterion weights were generated, and the sum of all these weights was found to be 1.

Table 2. Thematic layers and the data sources

Causative Factor	Data Source
Geomorphology	Geological Survey of India (1:250,000) https://bhukosh.gsi.gov.in/
Lithology	Geological Survey of India (scale 1: 2,000,000) https://bhukosh.gsi.gov.in/
Slope	SRTM- Digital Elevation Model (DEM) 30 × 30 m Resolution http://earthexplorer.usgs.gov/
Lineament Density	SRTM- Digital Elevation Model (DEM) 30 × 30 m Resolution http://earthexplorer.usgs.gov/
Drainage Density	SRTM- Digital Elevation Model (DEM) 30 × 30 m Resolution http://earthexplorer.usgs.gov/
Curvature	SRTM- Digital Elevation Model (DEM) 30 × 30 m Resolution http://earthexplorer.usgs.gov/
Rainfall	Climatic Research Unit (CRU) high-resolution gridded time series dataset at 0.5° resolution (2021-22) https://data.chc.ucsb.edu/products/CHIRPS-2.0/
Soil Texture	International Soil Reference and Information System (ISRIC) http://soilgrids.org
LULC	Landsat 8 OLI http://earthexplorer.usgs.gov/
Distance from the river	SRTM- Digital Elevation Model (DEM) 30 × 30 m Resolution http://earthexplorer.usgs.gov/
NDVI	Landsat 8 OLI http://earthexplorer.usgs.gov/
TWI	SRTM- Digital Elevation Model (DEM) 30 × 30 m Resolution http://earthexplorer.usgs.gov/

Table 3. Pairwise comparison matrix chart for all the factors developed for AHP-based groundwater potential zoning

Factors	Geomorphology	Lithology	Slope	Lineament Density	Drainage Density	Curvature	Rainfall	Soil	LULC	Distance from the river	NDVI	TWI
Geomorphology	1	1	2	3	4	4	3	4	4	4	5	5
Lithology	1	1	2	2	3	3	5	3	3	4	4	5
Slope	0.5	0.5	1	1	1	3	2	3	3	3	3	4
Lineament Density	0.33	0.5	1	1	1	4	5	3	3	1	4	4
Drainage Density	0.25	0.33	1	1	1	5	5	3	3	3	3	5
Curvature	0.25	0.33	0.33	0.25	0.2	1	3	3	1	3	0.5	1
Rainfall	0.33	0.2	0.5	0.2	0.2	0.33	1	2	0.5	2	2	3
Soil	0.25	0.33	0.33	0.33	0.33	0.33	0.5	1	0.5	3	2	1
LULC	0.25	0.33	0.33	0.33	0.33	1	2	2	1	1	1	2
Distance from the river	0.25	0.25	0.33	1	0.33	0.33	0.5	0.33	1	1	0.5	1
NDVI	0.2	0.25	0.33	0.25	0.33	2	0.5	0.5	1	2	1	2
TWI	0.2	0.2	0.25	0.25	0.2	1	0.33	1	0.5	1	0.5	1

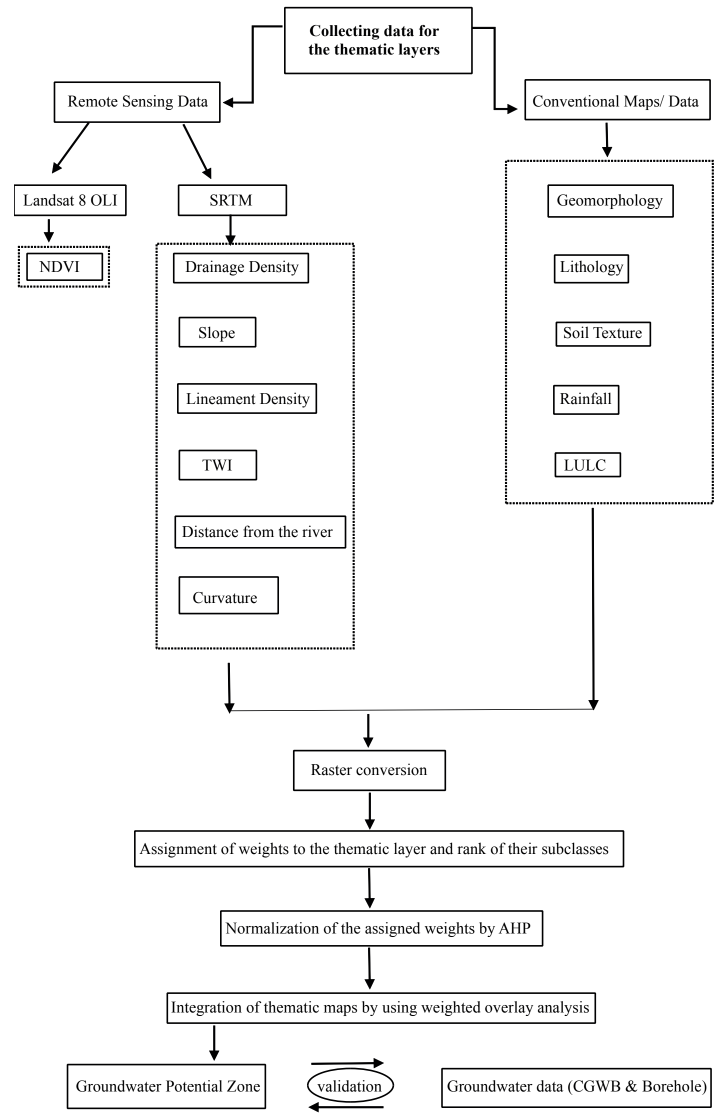

Fig. 2. Methodological Flowchart

Table 4. Description of the Saaty's scales for AHP based pair-wise comparison: (Saaty (1980))

Ratings	Degree of preferences	Descriptions
1	Equally	Both factors contribute equally
3	Moderately	Experiences and judgment slightly lean towards a specific factor
5	Strongly	Experiences and judgment strongly favor a particular factor over another
7	Very Strongly	One factor is strongly favored over another, and its dominance is shown in practice
9	Extremely	The preference of one factor over another is affirmed to the highest degree possible
2, 4, 6, 8	Intermediate values	Represents compromises between the preferences in ratings 1, 3, 5, 7, and 9

Table 5. Normalized pairwise comparison matrix and computation of criterion weight

Factors	Geomorphology	Lithology	Slope	Lineament Density	Drainage Density	Curvature	Rainfall	Soil	LULC	Distance from the river	NDVI	TWI	Criteria Weight
Geomorphology	0.21	0.19	0.21	0.28	0.34	0.16	0.11	0.15	0.19	0.14	0.19	0.15	0.19
Lithology	0.21	0.19	0.21	0.19	0.25	0.12	0.18	0.12	0.14	0.14	0.15	0.15	0.17
Slope	0.10	0.10	0.11	0.09	0.08	0.12	0.07	0.12	0.14	0.11	0.11	0.12	0.11
Lineament Density	0.07	0.10	0.11	0.09	0.08	0.16	0.18	0.12	0.14	0.04	0.15	0.12	0.11
Drainage Density	0.05	0.06	0.11	0.09	0.08	0.20	0.18	0.12	0.14	0.11	0.11	0.15	0.12
Curvature	0.05	0.06	0.04	0.02	0.02	0.04	0.11	0.12	0.05	0.11	0.02	0.03	0.05
Rainfall	0.07	0.04	0.05	0.02	0.02	0.01	0.04	0.08	0.02	0.07	0.08	0.09	0.05
Soil	0.05	0.06	0.04	0.03	0.03	0.01	0.02	0.04	0.02	0.11	0.08	0.03	0.04
LULC	0.05	0.06	0.04	0.03	0.03	0.04	0.07	0.08	0.05	0.04	0.04	0.06	0.05
Distance from the river	0.05	0.05	0.04	0.09	0.03	0.01	0.02	0.01	0.05	0.04	0.02	0.03	0.04
NDVI	0.04	0.05	0.04	0.02	0.03	0.08	0.02	0.02	0.05	0.07	0.04	0.06	0.04
TWI	0.04	0.04	0.03	0.02	0.02	0.04	0.01	0.04	0.02	0.04	0.02	0.03	0.03

Assessing the Consistency of the AHP model

The consistency of the weights assigned through a pairwise comparison matrix was assessed through the Consistency Index (*CI*) and Consistency Ratio (*CR*) following Eq. 1 and Eq. 2 respectively (Saaty 1980). The Consistency Index (*CI*) is dependent on the highest eigenvalue of the comparison matrix and the number of factors under consideration (Ying et al. 2007), while on the other hand Consistency Ratio (*CR*) is dependent on the Consistency Index (*CI*) and Random Index (*RI*) as suggested by Saaty 1980.

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

where, λmax principal eigenvalue and n is the no. of factors

$$CR = \frac{CI}{RI} \quad (2)$$

where *RI* is the Random Index value (Table 4) and *CI* is the Consistency Index

According to Saaty 1980, "the *CR* value should be ≤ 0.1 to continue with further analysis. If it is greater than 0.1, then the inconsistency needs to be ascertained and the calculations need to be revised". In the case of the present study, *CR* values of ≤ 0.1 overall as well as each parameter (Table 7) suggest that there exists a high level of consistency in assigning weight and thus, these assigned weights were further utilized for the identification of the Potential Groundwater Zones in the Lakhimpur District, Assam.

Table 6. Random index value (Saaty 1980)

1	2	3	4	5	6	7	8	9	10	11	12
0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

Table 7. Consistency analysis overall and individual parameter

Thematic Layers	λ max	N	RI	CI	CR	Consistency Statement
GWPZ	13.09	12	1.48	0.098	0.066	CR < 0.1 (Very Consistent)
Geomorphology	6.08	6	1.24	0.016	0.013	
Lithology	8.24	8	1.41	0.035	0.025	
Slope	5.21	5	1.12	0.054	0.048	
Lineament Density	5.12	5	1.12	0.031	0.028	
Drainage Density	5.07	5	1.12	0.018	0.016	
Curvature	5.23	5	1.12	0.059	0.053	
Rainfall	5.07	5	1.12	0.019	0.017	
Soil	6.22	6	1.24	0.045	0.036	
LULC	7.18	7	1.32	0.046	0.035	
Distance from the river	5.05	5	1.12	0.012	0.011	
NDVI	5.17	5	1.12	0.044	0.039	
TWI	5.21	5	1.12	0.053	0.047	

Where, *λ* max is the Maximum eigenvalue, *N* Number of factors, *RI* Random index, *CI* Consistency Index, *CR* Consistency ratio.

Delineation of Potential Groundwater Zones

The groundwater potential regions were identified using weighted overlay analysis methods in the ArcGIS environment (Aykut 2021). The weight assigned to all the causative factors and their sub-classes rated by their level of significance are depicted in Table 6. The groundwater potential index (GWPI) for the Lakhimpur district was calculated as shown in Eq. 3.

$$GWPI = GMw\,.\,GMr + Lw\,.\,LR + SLw\,.\,SLr + LDw\,.\,LDr + DDw\,.\,DDr + Cw\,.\,Cr + Rw\,.\,Rr + Sw\,.Sr + LULCw\,.\,LULCr + DRw\,.\,DRr + NDVIw\,.\,NDVIr + TWIw\,.\,RWIr \quad (3)$$

where *GM* is geomorphology, *L* is lithology, *SL* is a slope, *LD* denotes lineament density, *DD* is drainage density, *C* is curvature, *R* signifies rainfall, *S* represents soil, *LULC* indicates land use and land cover, *DR* is Distance from the river, *NDVI* represents Normalized Difference Vegetation Index and *TWI* is topographic wetness index. The suffix *w* represents weight, while *r* indicates the rank of each layer, respectively.

Validation of the groundwater potential zone map (GWPM)

For the validation purpose, 30 sample data from the observation well of the Central Groundwater Board and Borehole were utilized in the accuracy assessment of the groundwater potential map in accordance with the average water level (mbgl). The sample data were overlaid upon the groundwater potential zone map in ArcGIS software to verify the correspondence between them. A remark of 'agree' means that there is consensus between collected value and groundwater potential classes, whereas, a remark of 'partially agree' and 'disagree' means there is a dissonance (Table 9). Thus, the quantification of accuracy was possible following this method using Eq. 4 (Das and Mukhopadhyay 2020; Sajil Kumar et al. 2022)

$$GWPM\ Accuracy\ (\%) = \frac{Number\ of\ Agreement\ Samples}{Total\ Numner\ of\ Samples} \times 100 \quad (4)$$

Data from 12 available observation wells of *CGWB* were also used to show the groundwater level fluctuation during the Pre-monsoon (January to March 2022) and Post-monsoon (October to December 2022) (Table 10). The Receiver Operating characteristics (ROC) curve was used to evaluate the preciseness and reliability of the groundwater potential map by comparing it with the

Table 8. Assigned weights and ranks of all thematic layers through AHP

Causative Factors	Classes	Rank	Weight	Influence (%)
Geomorphology	Flood Plain	5	0.19	19
	Highly Dissected Hills and Valleys	1		
	Alluvial plain	4		
	Piedmont Slope	2		
	Waterbodies-River	5		
	Waterbodies-Other	5		

Lithology	White to greyish sand, silt, pebble and clay	4	0.17	17
	Unstabilised & Unoxidized Sand, Silt and Clay	5		
	Unoxidised Sand, Silt and Clay	5		
	Oxidised to feebly oxidised Sand, Silt and Clay	3		
	Highly Oxidised dark brown to red brown Loamy Sand	2		
	Sandstone, Clay, Comglomerate, Coal & Fossil wood	4		
	Gneiss/ Quartzite Pebbles in oxidised Sand, Silt and Clay	1		
	Cobble Pebble rich dark brown to reddish brown SST	2		
Slope	Very Low (0 - 0.92)	5	0.11	11
	Low (0.92 - 2.99)	4		
	Moderate (2.99 - 6.68)	3		
	High (6.68 - 11.89)	2		
	Very High (11.89 - 29.41)	1		
Lineament Density	Very Low (0 - 3.41)	1	0.11	11
	Low (3.41 - 9.66)	2		
	Moderate (9.66 - 15.20)	3		
	High (15.20 - 22.02)	4		
	Very High (22.02 - 36.23)	5		
Drainage Density	Very Low (0 - 7.31)	5	0.12	12
	Low (7.31 - 19.60)	4		
	Moderate (19.20 - 31.89)	3		
	High (31.89 - 46.23)	2		
	Very High (46.23 - 74.62)	1		
Curvature	-1.27 to - 0.20	5	0.05	5
	-0.20 to - 0.03	4		
	-0.03 to 0.04	3		
	0.04 to 0.24	2		
	0.24 to 1.40	1		
Rainfall	3463.57 to 3691.10	1	0.05	5
	3691.10 to 3870.74	2		
	3870.74 to 4062.34	3		
	4062.34 to 4261.94	4		
	4261.94 to 4481.49	5		
Soil	Waterbodies	5	0.04	4
	Cambisols	4		
	Fluvisols	5		
	Gleysols	2		
	Luvisols	3		
	Vertisols	1		

LULC	Waterbodies	5	0.05	5
	Dense forest	5		
	Shrub land	4		
	Agriculture	3		
	Built-up area	2		
	Sand bar	5		
	Barren land	1		
Distance from the river	Upto 200	5	0.04	4
	200 to 500	4		
	500 to 1000	3		
	1000 to 2000	2		
	Above 2000	1		
NDVI	-0.172 to 0.007	1	0.04	4
	0.007 to 0.106	2		
	0.106 to 0.179	3		
	0.179 to 0.247	4		
	0.247 to 0.447	5		
TWI	5.244 to 9.081	1	0.03	3
	9.081 to 10.747	2		
	10.747 to 12.847	3		
	12.847 to 15.888	4		
	15.888 to 23.708	5		

actual observed data. The ROC analysis is the most popular technique used in the evaluation of the effectiveness of various methods applied for groundwater suitability zone mapping (Pourtaghi and Pourghasemi 2014). The ROC plot is a graphical representation showing the relationship between the true positive (sensitivity) and false positive (1-specificity) rates (Shelar et al. 2023). The value usually ranges from 0.5 to 1.0 analysed through the Area Under the Curve (AUC), where a value of 0.5 indicates that the model is less significant in assessing groundwater potential whereas, a value near 1 indicates better accuracy (Pande et al. 2021).

Table 9. Location, groundwater level, and agreement with groundwater potential map

Sl. No.	Location Name	Longitude	Latitude	Source	Avarege Water level (mbgl)	Reference Class	Map Class	Agreement
1	Bhogpur charali	93.834	27.030	CGWB	1.77	G	M	Disagree
2	Basudeothan	94.357	27.260	CGWB	3.16	P	G	Disagree
3	Bihpuria	93.911	27.034	CGWB	2.43	M	M	Agree
4	Boginadi (balijan)	94.188	27.391	CGWB	1.44	G	G	Agree
5	Dolanghat chara	94.003	27.167	CGWB	1.54	G	G	Agree
6	Harmoti	93.856	27.126	CGWB	2.28	M	G	Partially Agree
7	Kadam	94.155	27.296	CGWB	1.16	G	G	Agree
8	Laluk	93.908	27.129	CGWB	1.49	G	M	Disagree
9	N. Lakhimpur (old)	94.106	27.218	CGWB	2.43	M	M	Agree
10	Narayanpur	93.858	26.963	CGWB	2.09	M	M	Agree

11	Panigaon	94.113	27.119	CGWB	2.51	M	M	Agree
12	Pathalipam	94.281	27.442	CGWB	2.65	M	G	Partially Agree
13	Dhakuakhana	94.426	27.229	Borehole	2.19	G	G	Agree
14	Gumto Check Gate	93.807	27.136	Borehole	1.65	G	M	Partially Agree
15	Nowboicha	94.014	27.161	Borehole	1.43	G	G	Agree
16	Abeeda Pathar	94.594	27.347	Borehole	1.33	G	G	Agree
17	Ananda Bagan	94.224	27.446	Borehole	2.96	M	M	Agree
18	Surya Tea Estate	94.123	27.391	Borehole	3.62	P	G	Disagree
19	Naharani	93.990	27.000	Borehole	1.87	G	G	Agree
20	Bihpuria 2	93.915	27.018	Borehole	2.76	M	M	Agree
21	Banpurai	93.801	26.850	Borehole	1.42	G	G	Agree
22	Kekuri Bebejia NC	94.305	27.117	Borehole	2.07	M	M	Agree
23	No.2 Koroiguri	94.337	27.132	Borehole	2.2	M	M	Agree
24	Dhalpur	93.803	26.914	Borehole	2.56	M	M	Agree
25	Banderdawa	93.828	27.108	Borehole	2.27	M	G	Partially Agree
26	Simantapur	94.296	27.428	Borehole	2.34	M	M	Agree
27	Khanajan	94.029	27.222	Borehole	2.65	M	M	Agree
28	Chauldhowa	94.246	27.449	Borehole	2.19	M	M	Agree
29	Tarioni	94.161	27.404	Borehole	2.22	M	M	Agree
30	Borchapori	94.208	27.190	Borehole	1.65	G	G	Agree

Table 10. Groundwater level fluctuation for existing CGWB sites (pre-monsoon and post-monsoon)

Sl. No.	Location Name	Longitude	Latitude	Source	Avarege Water level (mbgl)	Pre-monsoon (mbgl) (Jan-March, 2022)	Post-monsoon (mbgl) (Oct-Dec, 2022)	Variation in water-level	Rise/ Fall
1	Bhogpur charali	93.834	27.030	CGWB	1.77	2.14	1.59	0.55	Rise
2	Basudeothan	94.357	27.260	CGWB	3.16	4.15	3.13	1.02	Rise
3	Bihpuria	93.911	27.034	CGWB	2.43	2.85	1.3	1.55	Rise
4	Boginadi (balijan)	94.188	27.391	CGWB	1.44	1.89	2.02	-0.13	Fall
5	Dolanghat chara	94.003	27.167	CGWB	1.54	1.32	1.47	-0.15	Fall
6	Harmoti	93.856	27.126	CGWB	2.28	3.03	1.55	1.48	Rise
7	Kadam	94.155	27.296	CGWB	1.16	1.51	0.99	0.52	Rise
8	Laluk	93.908	27.129	CGWB	1.49	1.92	1.01	0.91	Rise
9	N. Lakhimpur (old)	94.106	27.218	CGWB	2.43	3.23	3.17	0.06	Rise
10	Narayanpur	93.858	26.963	CGWB	2.09	2.52	1.4	1.12	Rise
11	Panigaon	94.113	27.119	CGWB	2.51	2.46	3.64	-1.18	Fall
12	Pathalipam	94.281	27.442	CGWB	2.65	2.83	2.54	0.29	Rise

RESULTS AND DISCUSSION

Geomorphology

Geomorphology is considered the most significant determining factor in the recharge and storage of groundwater (Ghosh and Sahu 2023). It significantly influences various hydrological and hydrogeological processes, namely runoff, water infiltration, and the aquifer recharge process (Abijith et al. 2020). The Lakhimpur District is characterized by different geomorphological landform units namely, alluvial plains (1454.01 km^2), flood plains (1211.44 km^2), highly dissected hills and valleys (83.97 km^2), piedmont slopes (30.73 km^2), rivers (213.97 km^2), and other water bodies (0.51 km^2) (Fig. 3a). The dominance of alluvial plains, flood plains, and waterbodies which is roughly 96% of the total geographical area signifies that the area has a high potential for groundwater storage and recharge and thus, was given higher weights whereas, the highly dissected hills and valleys and Piedmont slope which constitute roughly 3.84% area are considered least significant due to high surface runoff and lower recharge area and were therefore given lower weights (Table 8).

Lithology

Lithological characterization is vital in identifying groundwater potential zones as it regulates percolation (Muralitharan and Palanivel 2015; Murmu et al. 2018; Shaban et al. 2006). The lithological settings of the Lakhimpur District are divided into eight sub-classes based on their physical and chemical properties including, the Barpeta I formation consists of white to greyish sand, silt, pebble, and clay from the late Holocene period covering 881.34 km^2 (roughly 29%), the Barpeta II formation consists of unstabilized & unoxidized sand, silt and clay from the late Holocene period covers 1198.79 km^2 (around 40 %), the Hauli formation having unoxidized Sand, Silt, and Clay of the Holocene epoch spread across 77.03 km^2 (2.57%), the Sorbhog formation consisting of oxidised to feebly oxidised sand, silt and clay of Pleistocene to Holocene period covers 558.97 km^2 (18.67%), the Chapar formation with highly oxidised dark brown to red-brown loamy sand of Middle to Late Pleistocene period covers 7.11 km^2 (0.23%), the Kimin formation consists of sandstone, clay, conglomerate, coal, and fossil wood from the Pliocene to Pleistocene covers 97.47 km^2 (3.25%), the Corramore formation having gneiss/ quartzite pebbles in oxidized sand of Early Pleistocene spread across 35.49 km^2 (1.18%) and the Chapar formation consist of silt and clay and cobble pebble rich dark brown to reddish brown SST of Middle to Late Pleistocene covers the remaining 136.83 km^2 (4.57%) of the total area (Fig 3b.). The newer alluvium namely, the Barpeta and Hauli formations and the Kimin formation (part of Siwalik Himalayas) were given higher weight as the lithology provides ample opportunity for water to percolate and recharge the groundwater. The Corramore, Chapar, and Sorbhog formations dominated by older alluvium were given lower weight due to the compactness and consolidated properties obstructing the percolation of water and reducing the porosity (Table 8).

Slope

The topographical effect on the infiltration of surface water and the infiltration rate is directly related to the slope characteristics of the region (Abijith et al. 2020). The low slope angle represents a flat surface and is considered suitable for groundwater recharge as the water gets more time to percolate in the sub-surface region whereas, steep slopes are not considered suitable as water drains fast down the slope affecting percolation time (Ghosh and Sahu 2023). The Lakhimpur District is divided into five slope categories (Fig. 3c), namely, very low (0–0.92^0), low (0.92–2.99^0), moderate (2.99–6.68^0), high (6.68–11.89^0), and very high (11.89–29.41^0). The flat and gentle slopes were assigned higher weights and the steep and very steep slopes were assigned lower weights (Table 8).

Lineament Density

Lineaments are linear features that provide an idea about the underlying fault and fracture zones which are essential for groundwater movement and storage. The region with high lineament density signifies high porosity and permeability resulting in higher groundwater potential and vice-versa (Tolche 2021). The Lineaments were digitized manually from SRTM DEM images and were used to generate the final lineament density map in the ArcGIS environment. The obtained lineament density map was divided into five classes (Fig. 3d), namely, very low (0–3.41 km/km^2), low (3.41–9.66 km/km^2), moderate (9.66–15.20 km/km^2), high (15.20–22.02 km/km^2), and very high (22.02–36.23 km/km^2). The regions with high lineament density have a positive relationship with the recharge of groundwater and thus, were given higher weights and vice-versa. Table 8 shows the assigned weights and ranks.

Drainage Density

Drainage Density is defined as the ratio between the basin area and the sum of the length of all the streams in that particular river basin (Horton 1945). It is inversely related to permeability, making it a key parameter in groundwater potential assessment (Rizeei et al. 2019). Higher drainage density indicates insignificant groundwater recharge due to greater surface runoff and less infiltration and lower drainage density means more infiltration contributing to greater groundwater potential (Chenini and Ben Mammou 2010). Five drainage density classes were recognized (Fig. 3e), namely, very low (0- 7.31 km/km^2), low (7.31–19.60 km/km^2), moderate (19.60–31.89 km/km^2), high (31.89–46.23 km/km^2), and very high (46.23–74.62 km/km^2). Higher weights were assigned to the areas with low drainage density and lower weights were assigned to the areas with high density in the zonation of groundwater potential of Lakhimpur District (Table 8)

Curvature

Curvature describes the nature of earth's surface profile namely, concave and convex (Arunbalaji et al. 2019). According to Khoshtinat et al. 2019, "The curvature of a slope provides a better understanding of the subsurface hydrology dynamics, soil formation, and accumulation". The deceleration and accumulation of groundwater depend upon the curvature of that particular area (Nair et al. 2017). The derived curvature values of the Lakhimpur District range between – 1.27 to 1.40 (Fig 3.f). Flat surface (-0.03 to 0.04) covering 1482.51 km^2 (49.50%) dominates the region which is the result of denudational activity of the rivers flowing in this region. The concave slope (-1.27 to – 0.03) occupies nearly 863.45 km^2 (28.83 %) and the convex slope (0.04 to 1.40) occupies 648.69 km^2 (21.65%). High weights were provided to the concave slopes where water can accumulate and higher infiltration occurs, whereas, the low weights were given to the convex slopes due to their poor water retention capacity (Table 8).

Rainfall

The intensity and spatiotemporal distribution of the precipitation directly influence the quantity of groundwater recharge and thus, influence the groundwater potential (Şen 2015). Rainfall with low intensity and of longer duration enables higher infiltration whereas, high-intensity rainfall for short duration increases surface runoff and reduces infiltration (Das et al. 2022). Although the Lakhimpur district region receives a very high amount of annual rainfall, the rainfall map was categorized into five classes based on the intensity of rainfall (Fig. 3g), namely, very low (3463.57 – 3691.10 mm/yr), low (3691.10 to 3870.74 mm/yr), moderate (3870.74 to 4062.34 mm/yr), high (4062.34 to 4261.94 mm/yr), and very high (4261.94 to 4481.49 mm/yr). The highest rainfall areas have the highest groundwater potentiality and thereby, were provided with the highest weight and vice-versa. Table 8 shows the assigned ranks and weights for the rainfall map and its sub-categories.

Soil

Soil physical properties namely, texture, depth, and composition play a pivotal role in determining groundwater recharge which makes it a crucial component in identifying groundwater potential (Arulbalaji et al. 2019; Saade et al. 2021). According to Tesfaye 2010, "The degree of permeability, which is established by the interaction between infiltration rates, and runoff and the properties of the soil, defines the groundwater potential". Fig 3 h. depicts the soil types of the Lakhimpur District. The region contains five different types of soil such as Cambisols (2812.57 km^2), Fluvisols (89.54 km^2), Gleysols (11.31 km^2), Luvisols (1.21 km^2) and Vertisols (2 km^2). Out of these, Cambisols was found to be the most dominant type of soil covering almost 94 percent of the study area. Higher weightages were provided to the soil types with coarse to fine materials and a good drainage while lower weightages were provided to the soil types with more clay content and water saturation capacity leading to poor drainage (Table 8).

Land use and Land cover

Land use and Landcover are crucial determinants of the groundwater availability and its storage in any region. It provides various details on soil moisture, infiltration, surface drainage, and other available water resources that are required to identify groundwater zones (Kom et al. 2022). Forest areas have high groundwater potential whereas, built-up and bare soil have less groundwater potential (Sajil et al. 2022). The LULC map was prepared from Landsat 8 OLI image in ArcGIS 10.4 using a supervised image classification algorithm. The accuracy of the LULC map was accessed by computing a confusion matrix in spatial analyst tools using seventy (70) randomly generated points in the ArcGIS environment. The overall accuracy and kappa values stood at 88.57% and 0.86 respectively. Seven Land use/cover were categorized (Fog. 3 i) namely, waterbodies (192.22 km^2), dense forest (346.05 km^2), shrublands (4.54 km^2), agriculture (1708.62 km^2), built-up areas (563.07 km^2), sand bars (105.57 km^2), and barren land (74.54 km^2). Waterbodies, dense forests, and sand bars were provided the highest weight due to their greater role in groundwater recharge, whereas, the barren land was provided the lowest weight due to their poor water retention capacity (Table 8)

Distance from the river

River waters are the prime source of groundwater within a river basin aquifer, thus, the areas nearby to that of a river have a good probability of groundwater potential (Vrzel et al. 2018; Halder et al. 2020). The distance from the river map was derived by creating buffers of up to 200 m, 500 m, 1000 m, 2000 m, and above 2000 m using Analysis tools in ArcGIS 10.4. The map was classified into five categories namely, < 200m (171.63 km^2), 200 – 500 m (266.62 km^2), 500 – 1000 m (377.44 km^2), 1000 – 2000 m (773.57 km^2), and > 2000 m (1405.89 km^2). Fig. 3j displays the distance from the river map for the Lakhimpur District. The area nearby to the major waterbodies was provided higher weight and vice-versa (Table 8).

Normalized Difference Vegetation Index (NDVI)

NDVI helps in estimating the amount of vegetation present and the groundwater potential zones over any area (Parizi et al. 2020). NDVI values range from -1 to +1, with values close to 1 indicating dense and healthy vegetation, values close to 0 indicating sparse vegetation, and values close to -1 indicating an absence of vegetation (Hasanuzzaman et al. 2022). The NDVI map was prepared from Landsat 8 bands 4 and 5 using a raster calculator in ArcGIS 10.4. The range of NDVI values carries from – 0.17 to 0.44. The NDVI map was classified into five categories (Fig 3 k) namely, -0.172 to 0.007 (71.77 km^2), 0.007 to 0.106 (231.39 km^2), 0.106 to 0.179 (1226.15 km^2), 0.179 to 0.247 (974.47 km^2), and 0.247 to 0.447 (490.55 km^2). The findings suggest the vegetation cover of the region falls under the moderate category (Swarnim et al. 2023). The areas with higher NDVI values were provided higher weight and those areas which have lower NDVI values were given lower weightage (Table 8).

Topographic wetness index (TWI)

TWI is a commonly used technique to estimate the topographic control over hydrological processes, including the infiltration of groundwater (Sørensen et al. 2006). Generally, higher TWI values indicate a higher probability of groundwater potential (Nampak et al. 2014). According to Shekar and Mathew 2023, "Areas with low TWI are more prone to generating overland flow than facilitating groundwater recharge, owing to the hillslope effect". The TWI map was classified into five categories (Fig. 3l) namely, very low (5.244 to 9.081), low (9.081 to 10.747), moderate (10.747 to 12.847), high (12.847 to 15.888), and very high (15.888 to 23.708). The lower TWI values were provided with low weights and the higher TWI values were provided with comparatively higher weights. (Table 8).

Groundwater Potential Zone (GWPZ)

A groundwater potential zone map was prepared using the Analytical Hierarchy Process (AHP) considering twelve parameters providing relative weights to each factor for their influence in the groundwater prospect of the region. The estimated Groundwater Potential Zones map of the Lakhimpur District, Assam was divided into three classes (Fig. 4) namely, Poor, Moderate, and Good. The areas within different groundwater potential zones are depicted in Table. 11. The findings illustrate that moderate and good potential zones are mostly found in the region with more than 99% of area coverage. The good groundwater potential zones (covering 65.12% area) are mostly found in the northeast, east,

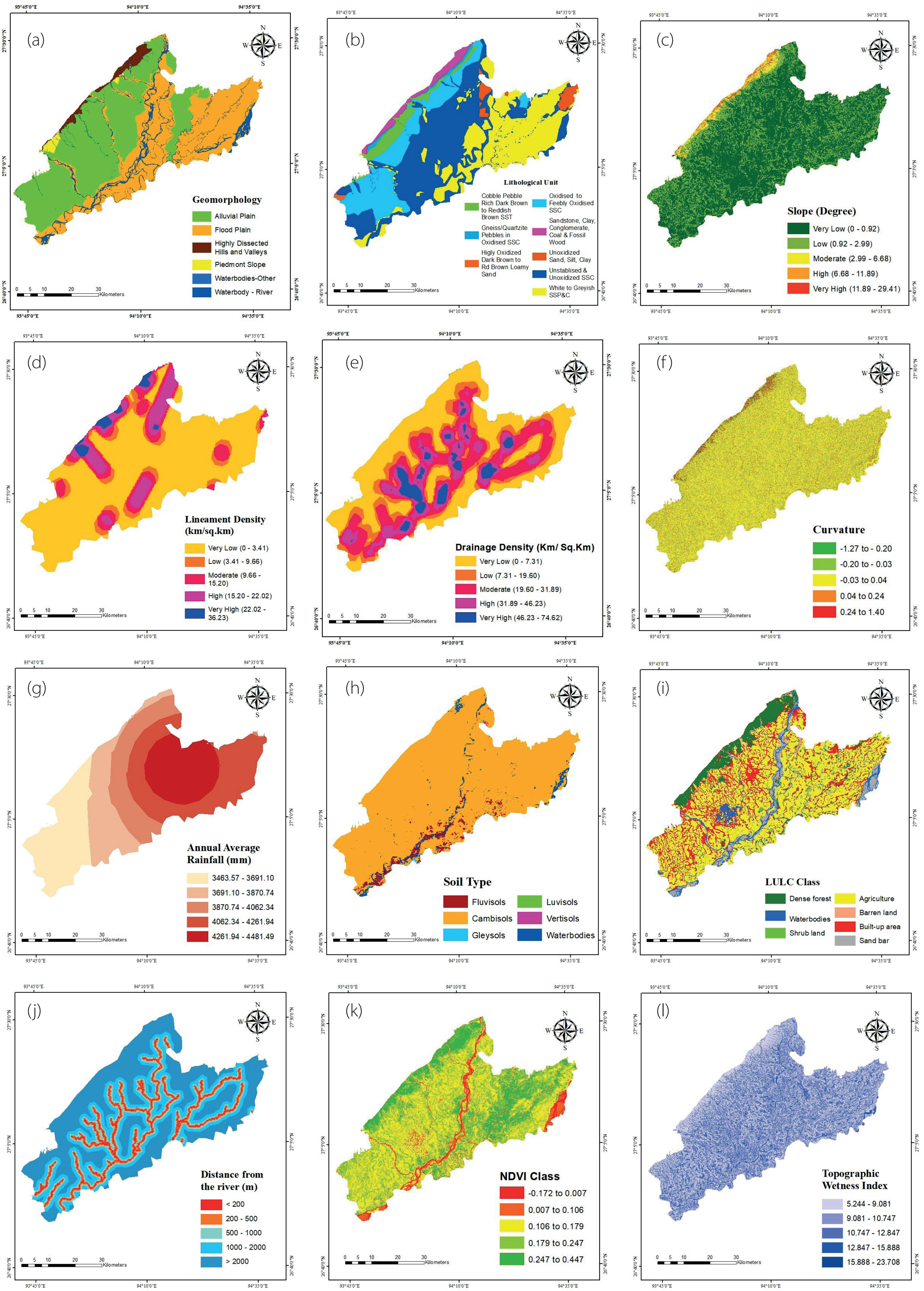

Fig. 3. (a) Geomorphological map; (b) Lithological map; (c) Slope map; (d) Lineament Density Map; (e) Drainage Density map; (f) Curvature map; (g) Average Annual Rainfall map; (h) Soil Type Map; (i) Land use and Landcover map; (j) Distance from the river map; (k) NDVI map; (l) TWI Map

southeast, and south corresponding to alluvial and floodplains, permeable materials, and lower slopes. There are some isolated pockets in the northern region where good groundwater potential was found because of the favourable geological structures, the existence of fault corridors, good drainage sources, and a high rate of infiltration. The zone of moderate groundwater potential covering 34.72% of the Lakhimpur District was found in the north, northwest, and western parts corresponding to the areas of moderately permeable rocks, moderate to low slope angle, presence of dense vegetation, and moderate drainage. Moreover, some isolated pockets of moderate potential zones were seen in the southeastern part of the region mainly covered with shrubs and permeable sediments. Poor groundwater potential zones were distributed in a small area (0.14%) in the northern portion mostly in the outer boundary of the Lakhimpur District where the highly dissected hills and valleys with high slope angles are present which favours more surface runoff and restrict infiltration.

Validation of the Outcome Map

The authentication and verification of the outcome are essential steps in evaluating the accuracy and credibility of any model. Without proper validation, models lack scientific significance (Das 2019; Chung et al. 2003). For validation of the groundwater potential map prepared using the Analytical Hierarchy Process (AHP) Model, this study used 30 ground truth data from twelve (12) observation wells of Central Groundwater Commission and eighteen (18) boreholes from various locations. The model validation process includes comparing the specific groundwater depth values with the groundwater potential map prepared using geospatial techniques. Table 9. shows the location of all the ground truth data points and the agreement status. The calculation process is stated as follows:

Number of ground sample data =30

Number of ground sample data that agreed with the result of the mapping = 22

Number of ground sample data that disagreed with the result of the mapping = 08

Overall accuracy of the GWP map = 22/30 ×100 = 73.33 %

The Receiver Operating Characteristics (ROC) curve was used to analyse the performance of the model. The model accuracy, as determined by the AUC – area under the curve, was ascertained to be 0.708. This analysis establishes that the global success rate of the groundwater map is 70.8% (Fig. 5). Therefore, it is affirmed that the approach employed in the present research exhibited favourable accuracy in mapping groundwater potential, exceeding the threshold of 70%.

Pre-monsoon and post-monsoon groundwater level data from twelve (12) observation wells of the Central Groundwater Board for the year 2022 were also used for validation of the GWP map (Table 10). The groundwater level in these stations during the pre-monsoon period ranges from 1.32 to 4.15 mbgl, while the groundwater level in the post-monsoon period ranges between 0.99 to 3.64 mbgl. The region with higher groundwater potential experiences minimal water level fluctuation and vice-versa (Bera et al. 2020). The region shows an average water level fluctuation of 0.50 mbgl between the pre-monsoon and post-monsoon periods (Fig. 6), indicating a reliable prediction of the moderate to good groundwater potential zones of the Lakhimpur District.

Table 11. Classification of Groundwater Potential Zones

GWP Classes	Area (km^2)	Area (%)
Poor	4.22	0.14
Moderate	1018.25	34.72
Good	1909.41	65.12

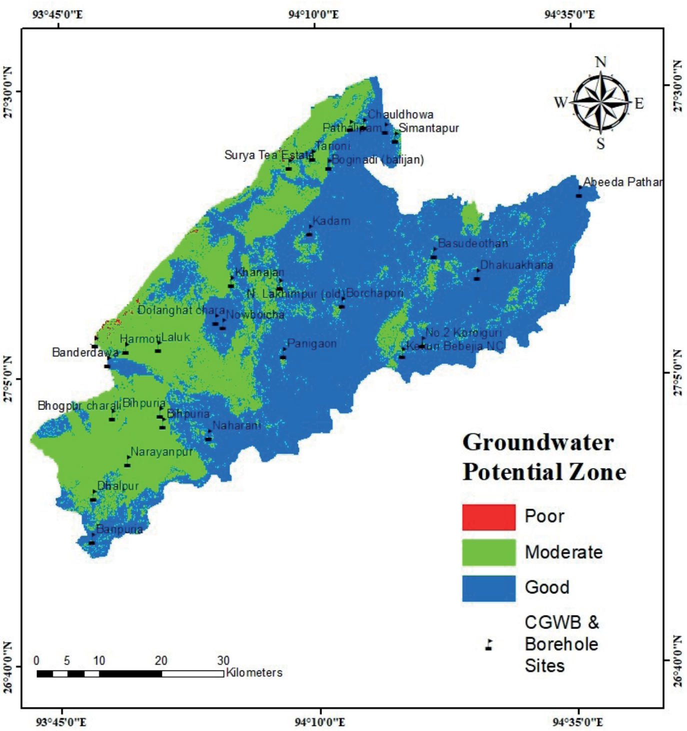

Fig. 4. Groundwater Potential Zone Map

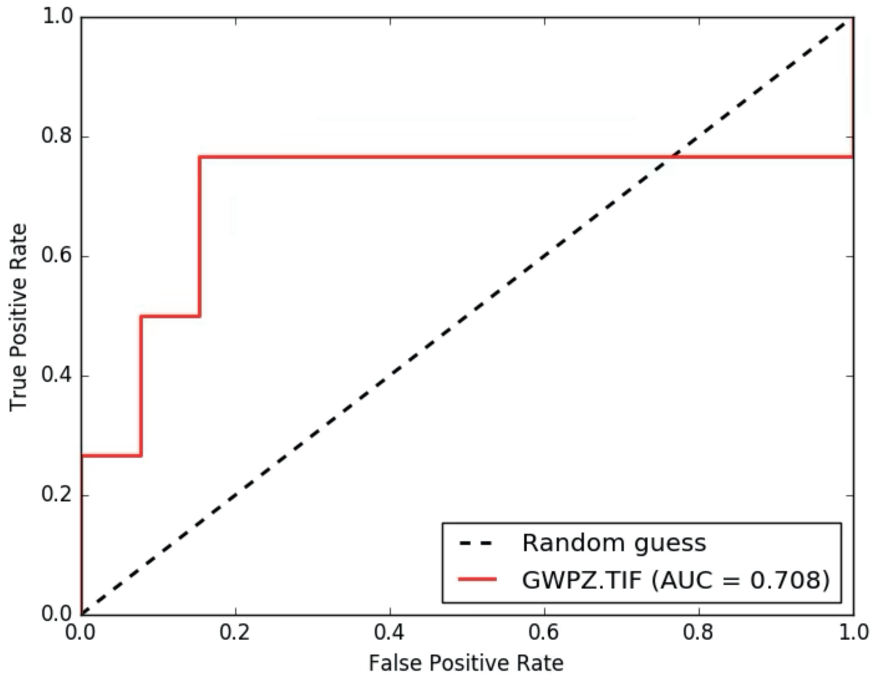

Fig. 5. ROC plot for the validation of groundwater potential zone map

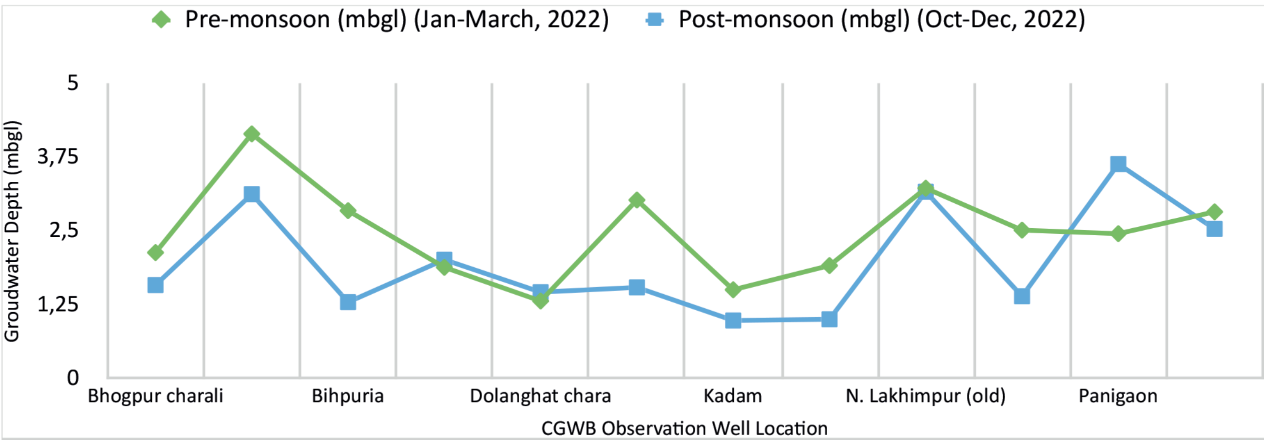

Fig. 6. Groundwater Level Fluctuation in various locations within the Lakhimpur District

CONCLUSIONS

This study attempted to assess the groundwater potential zones in Lakhimpur district, Assam, through the integration of remote sensing, GIS, and the Analytical Hierarchy Process (AHP) based multi-criteria decision-making techniques. The AHP technique was used to assign weights to the twelve factors considered for the research. The weights provided are based on the relative importance of each causative factor, determined using pair-wise comparison which were integrated into the GIS framework to produce the groundwater potential zone map. Among the factors, geomorphology and lithology were given higher weights compared to the others due to their significant roles in a fluvially originated landform, affecting infiltration rates, recharge processes, groundwater storage, and sedimentation. The resultant GWPZ map was classified into three categories: good, moderate, and poor zones, covering 1909.41 km^2 (65.12%), 1018.25 km^2 (34.72%), and 4.22 km^2 (0.14%), respectively. The findings revealed that the majority of the good potential zones are concentrated in the north, northeast, east, southeast, and southern directions, characterized by alluvial and floodplains, permeable and lower slope angles, and favourable geological conditions. The occurrence of moderate potential zones mainly in the west, northwest, and northern directions correspond with moderate permeability, moderate slope angles, and less dense vegetation cover. The areas with poor potential were found to be minimal, mostly located in the northern boundary marked by steep slopes and high surface runoff, which limits infiltration. The findings of the research were authenticated using groundwater level data derived from CGWB, field surveys, and the ROC method. The overall accuracy of 73.33%, ROC-AUC value of 0.708, and minimal water level fluctuation between pre-monsoon and post-monsoon periods suggest that the model performed well in identifying groundwater potential zones in the Lakhimpur District of Assam. The present study suggests that the use of geospatial techniques and AHP in groundwater potential zone identification is very effective and saves time and cost. Since the study area has a huge area under agriculture, the result will help in developing irrigation facilities and agricultural productivity. Lakhimpur District, Assam is experiencing a rapid rate of urbanization with a growing demand for freshwater for domestic and industrial purposes, the outcome of the research can be used by planners and policymakers for the identification of suitable groundwater sites and effective management of groundwater resources in the region.

REFERENCES

Abijith D., Saravanan S., Singh L., Jennifer J.J., Saranya T., and Parthasarathy K.S. (2020). GIS-based multi-criteria analysis for identification of potential groundwater recharge zones: a case study from Ponnaniyaru watershed, Tamil Nadu, India. HydroResearch, 3, 1–14. https://doi.org/10.1016/j.hydres.2020.02.002

Adimalla N. and Taloor A.K. (2020). Hydrogeochemical investigation of groundwater quality in the hard rock terrain of South India using Geographic Information System (GIS) and groundwater quality index (GWQI) techniques. Groundwater for Sustainable Development, 10:100288. https://doi.org/10.1016/j.gsd.2019.100288

Agarwal E., Agarwal R., Garg R.D., and Garg P.K. (2013). Delineation of groundwater potential zone: an AHP/ANP approach. Journal of Earth System Science, 122 (3), 887–898. https://doi.org/10.1007/s12040-013-0309-8

Ahmad I., Dar M.A., Andualem T.G., and Teka A.H. (2020). GIS-based multi-criteria evaluation of groundwater potential of the Beshilo River basin. Ethiopia. Journal of African Earth Science, 164:103747. https://doi.org/10.1016/j.jafrearsci.2019.103747

Arabameri A., Lee S., Tiefenbacher J.P., and Ngo P.T.T. (2020). Novel ensemble of MCDM-artificial intelligence techniques for groundwater potential mapping in arid and semi-arid regions (Iran). Remote Sensing, 12, (3), 490. https://doi.org/10.3390/rs12030490

Arulbalaji P., Padmalal D., and Sreelash K. (2019). GIS and AHP techniques based delineation of groundwater potential zones: a case study from Southern Western Ghats, India. Scientific Report, 9:1–17. https://doi.org/10.1038/s41598-019-38567-x

Aykut, T. (2021). Determination of groundwater potential zones using geographical information systems (GIS) and analytic hierarchy process (AHP) between Edirne-Kalkansogut (northwestern Turkey). Groundwater for Sustainable Development, 12, 100545. https://doi.org/10.1016/j.gsd.2021.100545

Benjmel K., Amraoui F., Boutaleb S., Ouchchen M., Tahiri A., and Touab A. (2020). Mapping of groundwater potential zones in crystalline terrain using remote sensing, GIS techniques, and multicriteria data analysis (Case of the Ighrem Region, Western Anti-Atlas, Morocco). Water, 12, (2), 471. https://doi.org/10.3390/w12020471

Bera A., Mukhopadhyay B. P., and Barua S. (2020). Delineation of groundwater potential zones in Karha river basin, Maharashtra, India, using AHP and geospatial techniques. Arabian Journal of Geosciences, 1315 (13), 1–21. http://dx.doi.org/10.1007/s12517-020-05702-2

Chakrabortty R., Pal S.C., Malik S., and Das B. (2018). Modeling and mapping of groundwater potentiality zones using AHP and GIS technique: a case study of Raniganj Block, Paschim Bardhaman, West Bengal. Modelling Earth System and Environment, 4 (3): 1085–1110. https://doi.org/10.1007/s40808-018-0471-8

Chenini I. and Mammou A.B. 2010. Groundwater recharge study in arid region: an approach using GIS techniques and numerical modeling. Computers and Geosciences, 36, (6) : 801–817. https://doi.org/10.1016/j.cageo.2009.06.014

Chung C. J. F. and Fabbri A. G. (2003). Validation of spatial prediction models for landslide hazard mapping. Natural Hazards, 30, 451-472. http://dx.doi172.62651.2b.org/10.1023/B:NHAZ.0000007

Dar T., Rai N., and Bhat A. (2020). Delineation of potential groundwater recharge zones using analytical hierarchy process (AHP). Geology, Ecology and Landscape, 5: 292–307. https://doi.org/10.1080/24749508.2020. 1726562

Das N., and Mukhopadhyay S. (2020). Application of multi-criteria decision making technique for the assessment of groundwater potential zones: a study on Birbhum district, West Bengal, India. Environment Development and Sustainability, 22 (2), 931–955. https://doi.org/10.1007/S10668-018-0227-7

Das S., and Pardeshi S.D. (2018). Integration of different influencing factors in GIS to delineate groundwater potential areas using IF and FR techniques: a study of Pravara basin, Maharashtra, India. Applied Water Science, 87, (8): 1–16. https://doi.org/10.1007/s13201-018-0848-x

Das, S. (2019). Comparison among influencing factor, frequency ratio, and analytical hierarchy process techniques for groundwater potential zonation in Vaitarna basin, Maharashtra, India. Groundwater for Sustainable Development, 8, 617-629. https://doi.org/10.1016/j.gsd.2019.03.003

Das, S., Mukherjee, J., Bhattacharyya, S. et al. (2022). Detection of groundwater potential zones using analytical hierarchical process (AHP) for a tropical river basin in the Western Ghats of India. Environmental Earth Science, 81, 416. https://doi.org/10.1007/s12665-022-10543-1

Deshpande, V. P., Sinha, M. K., and Shende, A. (2021). Identification of Critical Ground Water Potential Zones Using AHP & Geospatial Techniques. Design Engineering, 1774-1786.

Dwivedi C., Raza R., Mitra D., Pandey A., Jhariya D. (2021). Groundwater Potential Zone Delineation in Hard Rock Terrain for Sustainable Groundwater Development and Management in South Madhya Pradesh, India. Geography, Environment, Sustainability, 14 (1), 106-121. https://doi.org/10.24057/2071-9388-2020-195

Gautam V.K., Pande C.B., Kothari M, Singh P.K., and Agrawal A. 2023. Exploration of groundwater potential zones mapping for hard rock region in the Jakham river basin using geospatial techniques and aquifer parameters. Advances in Space Research, 71, (6): 2892–2908. https://doi.org/10.1016/j.asr.2022.11.022

Ghosh M., and Gope D. (2021). Hydro-morphometric characterization and prioritization of sub-watersheds for land and water resource management using fuzzy analytical hierarchical process (FAHP): a case study of upper Rihand watershed of Chhattisgarh State India. Applied Water Science, 11(2): 17. https://doi.org/10.1007/s13201-020-01340-x

Ghosh M., and Sahu A.S. (2023). Delineation of groundwater potential zones using AHP and GIS techniques: a case study in Barakar river basin, India. Arabian Journal of Geosciences. 16, 157. https://doi.org/10.1007/s12517-023-11253-z

Gopinath G., Nair A.G., Ambili G.K., and Swetha T.V. (2016). Watershed prioritization based on morphometric analysis coupled with multi criteria decision making. Arabian Journal of Geoscience, 9 (2): 129. http://dx.doi.org/10.1007/s12517-015-2238-0

Halder, S., Roy, M.B., and Roy, P.K. (2020). Fuzzy logic algorithm based analytic hierarchy process for delineation of groundwater potential zones in complex topography. Arabian Journal of Geoscience, 13 (13), 1–22. https://doi.org/10.1007/s12517-020-05525-1

Hasanuzzaman, M., Mandal, M.H., Hasnine, M. et al. (2022). Groundwater potential mapping using multi-criteria decision, bivariate statistic and machine learning algorithms: evidence from Chota Nagpur Plateau, India. Applied Water Science, 12, 58. https://doi.org/10.1007/s13201-022-01584-9

Horton R.E. (1945). Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geol Soc Am Bull 56 (3): 275–370 https://doi.org/10.1177/030913339501900406

Jari A., Bachaoui E. M., Jellouli A., Harti, A. E., Khaddari A., and Jazouli A. E. (2022). Use of GIS, Remote Sensing and Analytical Hierarchy Process for Groundwater Potential Assessment in an Arid Region – A Case Study. Ecological Engineering Environmental Technology, 23 (5), 234–255. https://doi.org/10.12912/27197050/152141

Jha M.K., Chowdary V.M., and Chowdhury A. (2010). Groundwater assessment in Salboni Block, West Bengal (India) using remote sensing, geographical information system, and multi-criteria decision analysis techniques. Hydrogeology Journal, 18, 1713–1728. https://doi.org/10.1007/s10040-010-0631-z

Khoshtinat S., Aminnejad B., Hassanzadeh Y., and Ahmadi H. (2019). Groundwater potential assessment of the Sero plain using bivariate models of the frequency ratio, Shannon entropy, and evidential belief function. Journal of Earth System Science, 128 (6), 152. https://doi.org/10.1007/s12040-019-1155-0

Kom, K.P., Gurugnanam, B. & Sunitha, V. (2022). Delineation of groundwater potential zones using GIS and AHP techniques in Coimbatore district, South India. International Journal of Energy and Water Resources. 1, 25. https://doi.org/10.1007/s42108-022-00188-y

Machiwal, D., Jha, M.K. and Mal, B.C. (2011). GIS-based assessment and characterization of groundwater quality in a hard-rock hilly terrain of Western India. Environmental Monitoring and Assessment. 174, 645–663. https://doi.org/10.1007/s10661-010-1485-5

Mahato, R., Bushi, D., Nimasow, G. et al. (2022). AHP and GIS-based Delineation of Groundwater Potential of Papum Pare District of Arunachal Pradesh, India. Journal of Geological Society of India. 98, 102–112. https://doi.org/10.1007/s12594-022-1936-y

Manap, M. A., Nampak, H., Pradhan, B., Lee, S., Sulaiman, W. N. A., and Ramli, M. F. (2014). Application of probabilistic-based frequency ratio model in groundwater potential mapping using remote sensing data and GIS. Arabian Journal of Geosciences, 7, 711-724. http://dx.doi.org/10.1007/s12517-012-0795-z

Melese T., and Belay T. (2022) Groundwater potential zone mapping using analytical hierarchy process and GIS in Muga Watershed, Abay Basin, Ethiopia. Global Challenges, 6: 2100068. https://doi.org/10.1002/gch2.202100068

Muralitharan J., and Palanivel K. (2015). Groundwater targeting using remote sensing, geographical information system and analytical hierarchy process method in hard rock aquifer system, Karur district, Tamil Nadu, India. Earth Science Informatics. 8, (4): 827–842. http://dx.doi.org/10.1007/s12145-015-0213-7

Murmu P., Kumar M., Lal D., and Sonker I. (2018). Singh SK (2019) Delineation of groundwater potential zones using geospatial techniques and analytical hierarchy process in Dumka district, Jharkhand, India. Groundwater for Sustainable Development. 9 :100239. https://doi.org/10.1016/j.gsd.2019.100239

Muth, K., and Sudalaimuthu K. (2021). Integration of Remote sensing, GIS, and AHP in demarcating groundwater potential zones in Pattukottai Taluk, Tamilnadu, India. Arabian Journal of Geosciences. 14, 1748 https://doi.org/10.1007/s12517-021-08110-2

Nair H. C., Padmalal D., Joseph A. and Vinod P. G. (2017). Delineation of groundwater potential zones in river basins using geospatial tools – an example from Southern Western Ghats, Kerala, India. J. Geo visualization Spatial Analysis. 1, 5. https://doi.org/10.1007/s41651-017-0003-5

Nampak H., Pradhan B., and Abd Manap M. (2014). Application of GIS based data driven evidential belief function model to predict groundwater potential zonation. Journal of Hydrology. 513, 283–300. https://doi.org/10.1016/j.jhydrol.2014.02.053

Oh H. J., Kim Y. S., Choi J. K., Park E., and Lee S. (2011). GIS mapping of regional probabilistic groundwater potential in the area of Pohang City, Korea. Journal of Hydrology. 399, 158–172. https://doi.org/10.1016/j.jhydrol.2010.12.027

Pande C.B., Moharir K.N., and Khadri S. (2021). Watershed planning and development based on morphometric analysis and remote sensing and GIS Techniques: A case study of semi-arid watershed in Maharashtra, India. In Groundwater resources development and planning in the semi-arid region. Cham: Springer. https://doi.org/10.1007/978-3-030-68124-1_11

Parizi E., Hosseini S. M., Ataie-Ashtiani B., and Simmons C. T. (2020). Normalized difference vegetation index as the dominant predicting factor of groundwater recharge in phreatic aquifers: case studies across Iran. Scientific Reports, 10, 17473. https://doi.org/10.1038/s41598-020-74561-4

Parthasarathy K. S. S., and Deka P.C. (2019). Remote sensing and GIS application in assessment of coastal vulnerability and shoreline changes: a review. ISH Journal of Hydraulic Engineering. 27, 588-600. https://doi.org/10.1080/09715010.2019.1603086

Pourtaghi Z.S., Pourghasemi H.R., (2014). GIS-based groundwater spring potential assessment and mapping in the Birjand Township, southern Khorasan Province. Iran. Hydrogeology Journal. 22, (3): 643–662. http://dx.doi.org/10.1007/s10040-013-1089-6

Qadir J., Bhat M.S., Alam A, and Rashid I. (2020). Mapping groundwater potential zones using remote sensing and GIS approach in Jammu Himalaya, Jammu and Kashmir. Geojournal 85, (2): 487–504. https://doi.org/10.1007/s10708-019-09981-5

Rizeei H.M., Pradhan B., Saharkhiz M.A., and Lee S. (2019). Groundwater aquifer potential modeling using an ensemble multi-adoptive boosting logistic regression technique. Journal of Hydrology. 579: 124172. https://doi.org/10.1016/j.jhydrol.2019.124172

Roy S., Hazra S., Chanda A., and Das S. (2020). Assessment of groundwater potential zones using multi-criteria decision-making technique: a micro-level case study from red and lateritic zone (RLZ) of West Bengal, India. Sustainable Water Resource Management. 6, (1), 1–14. https://doi.org/10.1007/s40899-020-00373-z

Saade J., Atieh M., Ghanimeh S. and Golmohammadi G. (2021). Modeling impact of climate change on surface water availability using SWAT model in a semi-arid basin: case of El Kalb River, Lebanon. Hydrology 8 (3), 134. https://doi.org/10.3390/hydrology8030134

Saaty T. L. (1980). The Analytic Hierarchy Process. McGrawhill, Juc. New York.

Sajil Kumar P.J., Elango L., and Schneider M. (2022). GIS and AHP Based Groundwater Potential Zones Delineation in Chennai River Basin (CRB), India. Sustainability, 14 (3), 1830. http://dx.doi.org/10.3390/su14031830

Saravanan S., Saranya T., Abijith D., Jacinth J. J., and Singh L. (2021). Delineation of groundwater potential zones for Arkavathi sub-watershed, Karnataka, India using remote sensing and GIS. Environmental Challenges, 5, 100380. https://doi.org/10.1016/j.envc.2021.100380

Şen Z. (2015). Applied drought modelling, prediction, and mitigation. Elsevier. https://doi.org/10.1016/C2014-0-01944-2

Shaban A., Khawlie M., and Abdallah C. (2006) Use of remote sensing and GIS to determine recharge potential zones: the case of Occidental Lebanon. Hydrogeology Journal. 14 (4): 433–443. http://dx.doi.org/10.1007/s10040-005-0437-6

Shekar P.R., and Mathew A. (2023). Integrated assessment of groundwater potential zones and artificial recharge sites using GIS and Fuzzy-AHP: a case study in Peddavagu watershed, India. Environmental Monitoring and Assessment. 195, 906. https://doi.org/10.1007/s10661-023-11474-5

Shekhar S., and Pandey A.P. (2014). Delineation of groundwater potential zone in hard rock terrain of India using remote sensing, geographical information system (GIS) and analytic hierarchy process (AHP) techniques. 30 (4), 402-421. Geocarto International. https://doi.org/10.1080/10106049.2014.894584

Shelar R. S., Nandgude S. B., Pande C. B., Costache R., El-Hiti G. A., Tolche A. D., ... and Yadav K. K. (2023). Unlocking the hidden potential: groundwater zone mapping using AHP, remote sensing and GIS techniques. Geomatics, Natural Hazards and Risk, 14 (1), 2264458. https://doi.org/10.1080/19475705.2023.2264458

Sorensen R., Zinko, U., and Seibert, J. (2006). On the calculation of the topographic wetness index: Evaluation of different methods based on feld observations. Hydrology and Earth System Sciences, 10, 101–112. https://doi.org/10.5194/hess-10-101-2006

Swarnim, Tripathi J.N., Sonker I. et al. (2023). Groundwater potential mapping in Trans Yamuna Region, Prayagraj, using combination of geospatial technologies and AHP method. Environmental Monitoring and Assessment. 195, 1375. https://doi.org/10.1007/s10661-023-11934-y

Tesfaye T. (2010). Ground water potential evaluation based on integrated GIS and RS techniques in Bilate river catchment, South rift valley of Ethiopia. American Scientific Research Journal for Engineering, Technology, and Sciences, 2313-4402. Global Society of Scientific Research and Researchers. Available from: http://asrjetsjournal.org

Tolche A. D. (2021). Groundwater potential mapping using geospatial techniques: A case study of Dhungeta-Ramis sub-basin, Ethiopia. Geology, Ecology, and Landscapes, 5 (1), 65–80. https://doi.org/10.1080/24749508. 2020.1728882

Vaddiraju S.C., and Talari R. (2023). Assessment of groundwater potential zones in Saroor Nagar watershed, Telangana, India, using geospatial techniques and analytical hierarchy process. Environment Science and Pollution Research. 30, 79758–79773. https://doi.org/10.1007/s11356-023-26185-0

Vrzel J., Solomon D. K., Blažeka Ž., and Ogrinc N. (2018). The study of the interactions between groundwater and Sava River water in the Ljubljansko polje aquifer system (Slovenia). Journal of Hydrology, 556, 384-396. https://doi.org/10.1016/j.jhydrol.2017.11.022

Ying X., Zeng G. M., Chen G. Q., Tang L., Wang K. L., and Huang D. Y. (2007). Combining AHP with GIS in synthetic evaluation of eco-environment quality—A case study of Hunan Province, China. Ecological modelling, 209, Issue 2-4, 97-109. https://doi.org/10.1016/j.ecolmodel.2007.06.007