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OPTIMIZING HYDROLOGICAL EXPLORATION THROUGH GIS-BASED GROUNDWATER POTENTIAL ZONING IN GOMATI DISTRICT, TRIPURA, INDIA

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ABSTRACT

This study evaluates groundwater availability using an integrated approach combining the Analytical Hierarchy Process (AHP), GIS and remote sensing techniques in Gomati District, Tripura. Diverse datasets including geology, rainfall, soil types, and remote sensing data are processed using Arc-GIS (Arc-map 10.3). These datasets are assigned weights according to Saaty's scale and subsequently normalized through the AHP. Arc-GIS overlay analysis shows that most of the Gomati district has excellent groundwater potential, with the good zone covering 81% (261.57 km²), the fair zone covering 16% (53.34 km²), and the excellent zone covering 3% (9.05 km²). Key findings indicate that lower drainage densities from the Debtamura hill range lead to higher groundwater potential due to increased infiltration. Dense vegetation and bare ground enhance recharge potential, while flatter terrains are more favorable for groundwater accumulation. Analyzing 33 years of rainfall data shows that higher altitudes receive more rainfall, further boosting groundwater potential.

Keywords: Arc-GIS, Groundwater, Slope analysis, Spatial tool, Remote sensing

INTRODUCTION

Groundwater serves as a vital resource for drinking, agriculture, and industry, and its distribution is influenced by several hydro-geological factors (Derdour et al., 2022). Approximately 30% of the global population relies on groundwater, with 50% of urban areas and 80% of rural areas using it for drinking purposes (Carrard et al., 2019). As the global population increases, the demand for fresh water has risen (Patel et al., 2023a; Verma et al., 2024). However, groundwater quality is deteriorating daily due to pollution, and groundwater levels are increasingly depleting (Abdelbaki et al., 2013; Bouchemal and Achour, 2015; Roy et al., 2020; Ihsan and Derosya, 2024). With increasing pressures on water resources due to population growth, agricultural demands, and climate change,

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a reliable groundwater potential map is crucial for developing strategies to manage water resources, mitigate water scarcity, and support agricultural and industrial activities (Adjim and Bensaoula, 2013; Abdelbaki et al, 2013; Drias and Toubal, 2015; Haouchine et al., 2015; Kerzabi et al., 2016; Zegait et al., 2021; Koussa and Berhail, 2021; Jaiswal et al., 2023). Such maps will aid in sustainable water resource management, ensuring that groundwater extraction is balanced with natural recharge rates. Providing decision-makers with high-quality, region-specific groundwater potential maps will also enable more informed and effective planning and policy-making.

The Analytical Hierarchy Process (AHP) offers a systematic methodology for evaluating and prioritizing multiple criteria (Wong and Li, 2008; Berrezel et al., 2023; Jaiswal et al., 2023; Mehta at al., 2023; Patel et al., 2023c). AHP facilitates the decomposition of complex decision-making problems into a hierarchy of simpler sub-problems. It has been widely utilized in various fields, including groundwater potential mapping (Khan and Samadder, 2015; Singh et al., 2021; Fatah and Mustafa, 2022; Patel et al., 2023d; Jaiswal et al., 2023; Abdulhaq et al., 2024). It involves structuring a problem into a hierarchy, comparing elements pair wise, and determining their relative weights based on expert judgment. In the context of groundwater studies, AHP helps in assigning weights to different thematic layers. These layers are crucial for assessing groundwater potential as they influence infiltration, storage, and movement of groundwater. A substantial body of research has demonstrated AHP's effectiveness in this domain (Kumar et al., 2015; Zyoud and Fuchs, 2017; Petruni et al., 2019; Wang et al., 2022; Verma et al., 2023). For instance, Arya et al. (2020) successfully employed AHP to delineate groundwater potential zones by weighting factors such as rainfall, slope, drainage density, and land use. Similarly, Abdullateef et al. (2021) highlighted the method's robustness in integrating remote sensing and GIS data to assess groundwater recharge potential. The adaptability of AHP allows for the inclusion of expert judgments, enhancing the accuracy of groundwater potential maps. Furthermore, the technique's transparency and consistency make it a preferred choice for resource management and planning.

Geographic Information System (GIS) and Remote Sensing (RS) offer an effective framework for collecting, analyzing, and visualizing spatial data (Coulibaly Talnan et al., 2016; Kerboub et al., 2016; Soro et al., 2020; Jamal et al., 2024). Remote sensing provides up-to-date and high-resolution imagery that is essential for identifying surface features related to groundwater recharge. GIS facilitates the incorporation of multiple spatial datasets, enabling the creation of thematic maps and the execution of overlay analyses (Srinivas et al., 2018). Nasiri et al. (2013) used these technologies to delineate groundwater recharge zones in Iran, highlighting the importance of integrating various data sources and analytical methods. Similarly, Bielecka (2020) utilized GIS-based models, emphasizing the role of accurate spatial data and advanced analytical techniques. In India, numerous studies have applied GIS and RS techniques for groundwater potential mapping (Patel et al., 2023b; Verma et al., 2023; Gohil et al., 2024; Mehta et al., 2024). Machiwal (2018) underscored the significance of incorporating multiple criteria in groundwater assessments. Similarly, Allafta et al. (2020) demonstrated the utility of GIS in regional groundwater studies.

Despite the significant advancements in groundwater potential mapping techniques, several gaps still remain, particularly concerning the specific hydro-geological and environmental contexts of regions like the Gomati District in Tripura. Most existing studies have focused on regions with relatively straightforward geological settings, often neglecting areas with complex topographies and diverse geological formations like those found in Gomati District (Debbarma et al., 2016; Debbarma and Nibedita, 2019; Karmakar et al., 2023). There is a lack of detailed, region-specific studies that address the unique challenges and characteristics of Tripura's groundwater system (Majumdar and Das, 2020). While various datasets (e.g., DEM, geological maps, rainfall data, soil types) are available, there is a need for more sophisticated methods of integrating these diverse data sources. Existing studies often use these datasets in isolation or through simplistic overlay techniques, which may not fully capture the intricate interactions between different hydrological factors.

The Gomati District in Tripura presents a unique set of challenges and opportunities for groundwater potential mapping. The district's diverse topography, varying climatic conditions, and complex geological structures necessitate a comprehensive and integrated approach. Studies focusing on this region have highlighted the need for detailed thematic maps and robust analytical frameworks (Paul et al., 2019; Roy et al., 2024). The present study introduces a comprehensive approach for mapping groundwater potential in Gomati District, Tripura. This approach integrates the AHP, GIS, and RS techniques. This research stands out by providing a region-specific analysis that addresses the unique hydro-geological and environmental characteristics of the area, filling a critical gap in groundwater studies in northeastern India. The study employs advanced integration techniques to assign precise weights to various thematic layers, utilizing comprehensive datasets such as DEM data, geological maps, rainfall data, soil type maps, and high-resolution Land sat imagery.

This study is the first to provide a detailed groundwater potential map for the Gomati District, offering valuable insights into the region’s hydro-geological characteristics. The study utilizes a combination of GIS, remote sensing (RS), and the Analytical Hierarchy Process (AHP) to assess groundwater potential, demonstrating the effectiveness of integrating these advanced tools for hydro-geological studies. The analysis identifies critical factors such as drainage density, slope, land use/land cover, and rainfall as key determinants of groundwater availability in the district. The zoning map provides a practical tool for policymakers, water managers, and local authorities to plan sustainable groundwater extraction, recharge efforts, and water resource conservation, thereby addressing the district’s groundwater challenges. The methodology presented in this study is replicable and can be applied to similar terrains in other regions, providing a framework for future groundwater exploration and management studies.

STUDY AREA

Gomati, a district in the north-eastern state of Tripura, is geographically located between latitudes N 23° 32' 2.364" and longitudes E 91° 28' 52.392" (Fig. 1). It is one of the eight districts in Tripura, India, with Udaipur as its headquarters. Established in January 2012, Gomati is administratively divided into two subdivisions—Udaipur and Amarpur. The district is named after the Gomati River, one of Tripura's largest rivers, which traverses its terrain. Gomati's topography features fertile valleys and the scenic Debtamura hill range, renowned for its ancient sculptural works. Elevations within the district range from 4 meters to 385 meters above sea level (Kakoti et al., 2019).

Gomati District experiences a warm and humid tropical climate, characteristic of the region. The district receives substantial annual precipitation, averaging around 2,096 mm (Debnath et al., 2024). This abundant precipitation supports the lush green valleys and the fertile agricultural lands of the district. The mean air temperature in Gomati varies significantly throughout the year, ranging from a mild 20°C to a hot 35°C (Ghosh et al., 2020). The district experiences three primary seasons: a hot summer, a monsoon period, and a mild winter. Summers, extending from March to May, are typically hot and humid, with temperatures often peaking in May. The arrival of the monsoon brings heavy rains, which significantly cool the region and sustain its greenery. Winters in Gomati, from December to February, are relatively mild and pleasant, with temperatures dropping to more comfortable levels. The diverse topography of Gomati, with elevations ranging from 4 meters to 385 meters, also contributes to slight microclimatic variations within the district.

METHODOLOGY

Mapping Thematic layers

In the present work, high-resolution satellite imagery is utilized to map groundwater zones by analyzing soil type, geology, rainfall, drainage density, lineament density, land use and cover, and slope. Using Arc-Map 3.0 in Arc-GIS, drainage networks are constructed from the DEM obtained from the USGS Earth Explorer site. These networks are produced through various analytical stages in Arc-GIS software, and classified into four numerically weighted categories as shown in Fig. 3. The groundwater prospects are classified as follows: very low for 0-1 km/km^2, low for 1.01-2 km/km^2, high for 2.01-3 km/km^2, and extremely high for 3.01-5 km/km^2. Areas with low drainage density receive high rankings due to the higher rate of infiltration. The methodological flowchart employed to recognize the zones with potential groundwater is shown in Fig. 2.

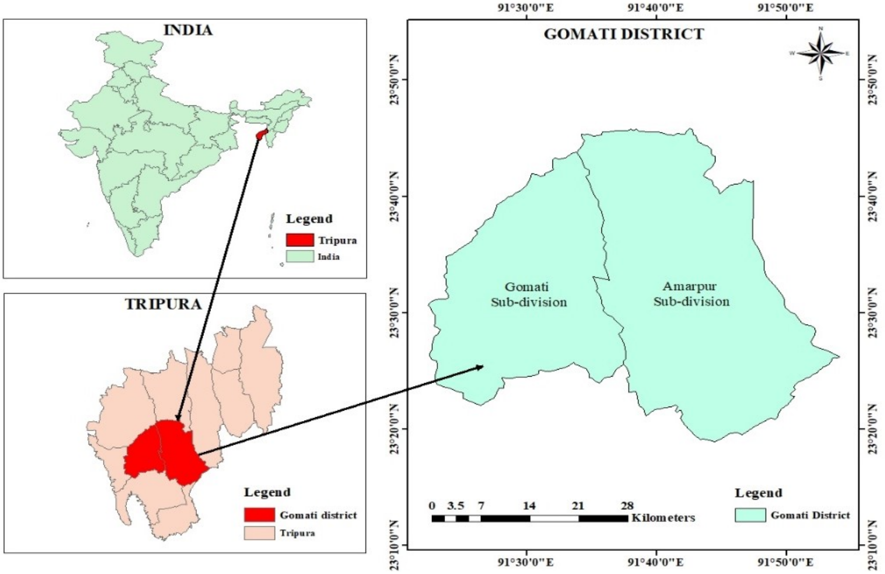

Figure 1: Study Area Map – Gomati District, Tripura

The raw soil data used to determine the soil types in the research area were obtained from the FAO website (https://www.fao.org/soils-portal/data-hub/en/). The Gomati District primarily composed of two main soil types: Sandy Loam and Loamy soil. Silt clay loam has mild to moderate permeability, while loamy sand exhibits very high permeability. Clay loam has low permeability, whereas sandy clay loam ranges from moderate to high permeability. For land use map classification, Landsat 8 images from the USGS Earth Explorer site were used, employing Landsat 8-9 OLI/TIRS C2L2 GeoTIFF data with spatial resolutions of 30m and 100m. The SRTM-DEM data has a resolution of about 30 meters. This data was used to prepare maps showing slope, lineaments, and drainage patterns. Climatic Research Unit data was used for rainfall analysis to create the rainfall map.

Assigning and normalizing weights

AHP involves making pair wise comparisons among elements at each level to determine their relative importance, generating numerical priorities for each element (Saaty and Shang, 2011). These comparisons are aggregated to calculate overall priorities for the decision alternatives using mathematical techniques. A consistency check ensures the logical soundness of the judgments, with a consistency ratio below 0.1 indicating acceptable consistency. AHP is widely used for resource allocation, strategic planning, and other complex decision-making scenarios due to its ability to systematically analyze multiple criteria and alternatives. The AHP methodology involves the following steps (Leal, 2020):

1. To find the total of the values in each column of the comparison table, we use a specific formula for adding up all the numbers in that column:

$$L_j = \sum_{ij=1}^{n} Cij \qquad (1)$$

L_j= computed sums of values in each column

C_{ij}= specific numerical value allocated to each criterion

Then divide each number in the matrix by the total of its column

$$Xij = \frac{C_{ij}}{L_j} \qquad (2)$$

2. Where X_{ij}= the calculated value of the normalized pair-wise matrix reflecting the normalization process
3. To find the standard weights, add up all the numbers in each row of the matrix after they have been adjusted and divide that total by the number of criteria (N).

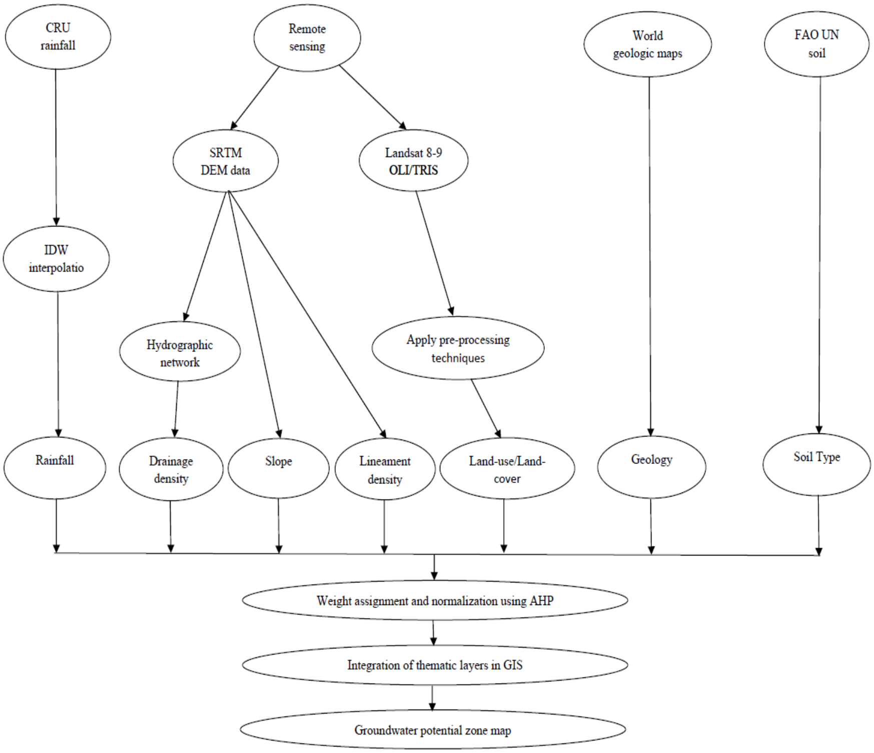

Figure 2: The methodological flowchart employed to recognize the zones with potential groundwater.

Consistency Analysis

The pair-wise comparison matrix values and normalized pair-wise matrix values of thematic layers are multiplied by corresponding values using matrix multiplication to determine the consistency vector (Kumar et al., 2022). The corresponding calculation and its process are shown below with tables of consistency analysis process (Table 5 and 6).

$$Wi = \sum \frac{K_{ij}}{N} \tag{3}$$

4. Where X_{ij}= standard weight.

The formula used to calculate the Consistency factor (λ) is as follows:

$$\lambda = \sum \left(C_{ij} X_{ij} \right) he \tag{4}$$

Consistency Index (CI) to quantify the extent of deviation or consistency, was computed as (Brunelli, 2017):

$$CI = \frac{\lambda - n}{N - 1} \tag{5}$$

Consistency ratio (C_r) was calculated as $(CI/\ RI)$, where, RI = Reliability index.

The criterion for determining the acceptability of inconsistency is based on the Consistency Ratio ≤ 0.1; adjustments to subjective judgments are necessary otherwise. A 9-point scale: 1, 3, 5, 7, and 9 represent significant, quite significant, highly significant, extremely significant, and very strongly significant, respectively. Intermediate values (2, 4, 6, and 8) were used for compromises. Each factor was given a rate indicating its potential for groundwater, using a scale from 1 to 4, where 1 stands for poor, 2 for fair, 3 for good, and 4 for excellent potential. Table 3 displays the random inconsistency values for n different criteria. The calculated Consistency ratio (C_r) = 0.0395 < 0.10.

For the proportion of inconsistency, it is presumed that the matrix is reasonably consistent. Therefore, AHP may continue to be utilized in the decision-making process. Considering the requirements of the study area, these weights for criteria might be applied by the decision maker for further calculation.

Table 1: The scale of significant parameters for Pair wise Comparison Matrix

Significant Strength	Importance
1	Equal
3	Medium
5	Strong
7	Very strong
9	Maximum
2,4,6, and 8	Interval number between two consecutive numbers

Table 2: Random indices for matrices of various sizes (Satty, 1990)

n	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 3: The matrix for comparing the seven thematic layers

	R	**G**	**S**	**DD**	**LU/LC**	**LD**	**ST**
R	1	3	3	5	5	5	7
G	0.33	1	3	3	5	5	5
S	0.33	0.33	1	1	3	3	5
DD	0.2	0.33	1	1	1	2	3
LU/LC	0.2	0.2	0.33	1	1	1	3
LD	0.2	0.2	0.33	0.5	1	1	1
ST	0.14	0.2	0.2	0.33	0.33	1	1
Sum total	2.4	5.26	8.86	11.83	16.33	18	25

Table 4: The matrix for comparing the seven thematic layers after normalization

	R	**G**	**S**	**D**	**LU/LC**	**LD**	**ST**	**Criteria weights**
R	0.4166	0.5703	0.3386	0.4226	0.3061	0.2777	0.2800	0.3731
G	0.1375	0.1901	0.3386	0.2535	0.3061	0.2777	0.2000	0.2433
S	0.1375	0.0627	0.1128	0.0845	0.1837	0.1666	0.2000	0.1354
DD	0.0833	0.0627	0.1128	0.0845	0.0612	0.1111	0.1200	0.0908
LU/LC	0.0833	0.0380	0.0372	0.0845	0.0612	0.0555	0.1200	0.0685
LD	0.0833	0.0380	0.0372	0.0422	0.0612	0.0555	0.0400	0.0510
ST	0.0583	0.0380	0.0225	0.0278	0.0202	0.0555	0.0400	0.0374

Table 5: Calculation of consistency

	R	**G**	**S**	**DD**	**LU/ LC**	**LD**	**ST**	**Weight Value**	**Criteria weights**
R	0.373	0.729	0.406	0.454	0.342	0.255	0.261	2.822	0.373
G	0.123	0.243	0.406	0.272	0.342	0.255	0.187	1.829	0.243
S	0.123	0.080	0.135	0.090	0.205	0.153	0.187	0.975	0.135
DD	0.074	0.080	0.135	0.090	0.068	0.102	0.112	0.663	0.090
LU/LC	0.074	0.048	0.044	0.090	0.068	0.051	0.112	0.490	0.068
LD	0.074	0.048	0.044	0.045	0.068	0.051	0.037	0.370	0.051
ST	0.052	0.048	0.027	0.029	0.022	0.051	0.037	0.268	0.037

Table 6: Weighted ratio calculation of different criteria

Value of Weighted Sum	Weights of Criteria	$\frac{\text{Weighted sum value}}{\text{Criteria weights}}$
2.8225	0.3731	7.5649
1.8295	0.2433	7.5195
0.9750	0.1354	7.2008
0.6637	0.0908	7.3094
0.4903	0.0685	7.1576
0.3701	0.0510	7.2568
0.2687	0.0374	7.1844

Evaluation of zones with potential for groundwater

The methodology for evaluating zones with potential for groundwater involves several key steps. Initially, relevant data layers are collected and analyzed using the Arc-GIS software. Next, these layers are combined and assessed through the AHP. Slope, drainage patterns, and lineament maps are generated to identify areas with favourable conditions for groundwater recharge. The final potential zones are mapped by integrating these analyses, providing a comprehensive overview of regions most likely to support groundwater resources. Groundwater potential zones were recognized utilizing the linear weighted combination approach. The following formula is utilized to calculate the Total Scores (Pande et al., 2021):

$$TS = \sum W \times R \tag{6}$$

Where W is the weights of the features and R is the weight of the thematic layer, respectively, and TS = Total Scores using the information on the criteria's ranking.

RESULTS AND DISCUSSION

In this study, the unprocessed remote sensing data were collected and analyzed in the Arc-GIS 10.3 software. The raw data included DEM (Digital Elevation Model) from the USGS Earth Explorer website, Landsat 8-9 OLI/TIRS, C2L2, and Geo-TIFF data, geological map shape files from the World Geological Maps website and soil shape files from the FAO website. These data sets were integrated to analyze and create the necessary maps influencing the Groundwater availability in the Gomati District. The DD map and the LD map have been derived from the DEM. The LU/LC map was produced using Landsat-9 satellite data, the Geology map was based on geological shape files, the Rainfall map utilized precipitation statistics from Climate Research, and the Soil map was developed from the soil shape file.

Drainage Density (DD)

Drainage pattern plays a key role in ground water formation. Runoff increases if drainage density is higher. As a result, there will be less water intrusion there. Infiltration will increase if drainage density is lower. Thus, a zone with groundwater potential may exist. This study's drainage flows originate from Debtamura hill range which straddles Udaipur and Amarpur subdivisions. The drainage characteristics in this area are similar to dendrite. The tightness of the channel spacing is known as drainage density. With the aid of Arc-Map 3.0 of Arc-GIS, the drainage networks are built from the DEM taken from the USGS Earth Explorer site. Then, using Arc-GIS software, these extracted networks are produced by going through a number of analytical stages. The DD map derived in this work is presented in Fig. 3. There is very little ground water prospect under 0-1 km/km^2, low ground water prospect under 1.01-2 km/km^2, high ground water prospect under 2.01-3 km/km^2, and extremely high ground water prospect under 3.01-5 km/km^2. Low drainage density receives high rankings because of a higher rate of infiltration.

Land-use/Land-cover (LU/LC)

The USGS Explorer site provides Landsat 8 images that are used to classify land use maps. The NDVI values that fall between 0.1 and 0.6 for vegetation and ranges from -1 to +1. Dense vegetation is indicated if the value is more than 0.4. There is no vegetation, or bare ground, if the value is less than 0.15. Wet places or bodies of water may be indicated if the value is 0. Using the formula below, the Normalized Different Vegetation Index (NDVI) is determined as:

$$NDVI = \frac{NIR-RED}{NIR+RED} \tag{7}$$

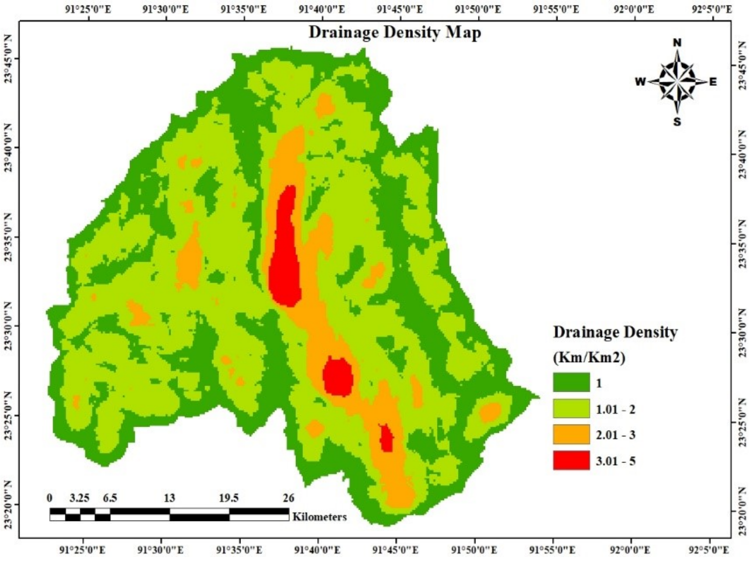

Figure 3: Drainage Density Map of Gomati District, Tripura

LU/LC determines the groundwater potential in a region as they directly influence the infiltration characteristics. For instance, areas with dense vegetation or forests typically facilitate higher groundwater recharge due to better infiltration and reduced runoff, while urbanized areas with impervious surfaces can hinder recharge and increase runoff. Understanding land cover patterns helps in assessing how water is distributed and replenished across different landscapes, enabling more accurate identification of zones with high groundwater potential and aiding in effective water resource management. The LU/LC map derived in this study is presented in Fig. 4.

Slope (S)

The slope map reveals the gradient of the land surface, which affects water flow and infiltration rates. Steeper slopes often lead to increased surface runoff and reduced infiltration, which can limit groundwater recharge and reduce the potential for groundwater accumulation. Conversely, gentler slopes typically allow for better water infiltration and recharge, making these areas more suitable for groundwater development. By analyzing slope maps, it becomes possible to identify areas with optimal gradients for groundwater recharge and to avoid regions where excessive runoff might diminish groundwater potential. This slope map is crucial for identifying and prioritizing areas with sustainable water resources. In terms of percentage, the slope map was divided in four categories: flat (1%), moderate (1.01-2%), medium (2.01-3%), and steep (3.01-55%) as shown in Fig. 5. The slopes that are level and moderate are given the highest weight. Slopes that are steep or extremely steep are given a low weight.

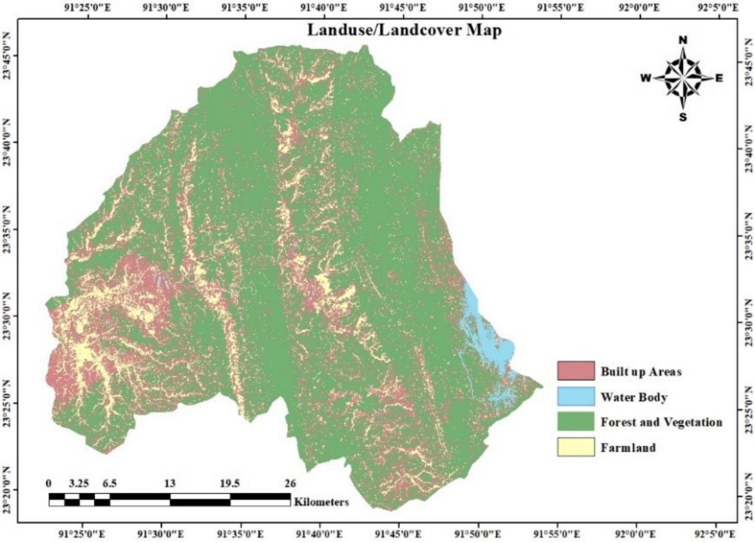

Figure 4: The LU/LC Map of Gomati District, Tripura

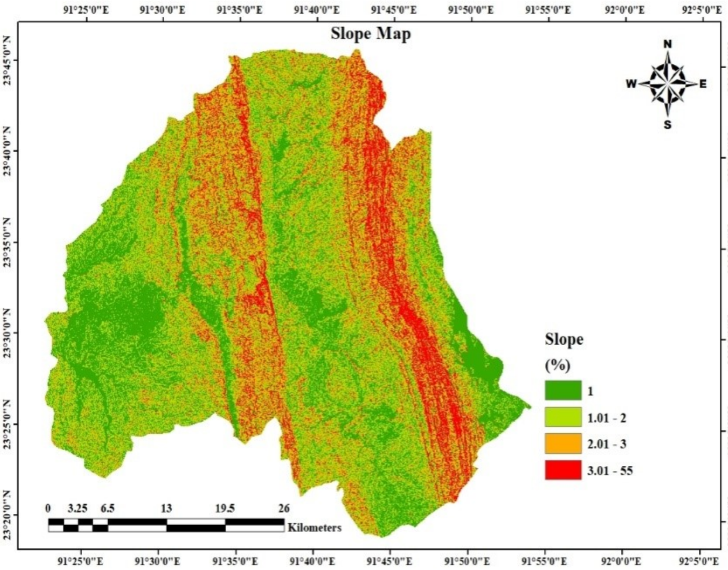

Figure 5: Slope Map of the Gomati District, Tripura

Lineament Density (LD)

This map is significant in determining the presence of groundwater because it provides the salient features such as faults, fractures, and joints, which influence groundwater movement and accumulation. High lineament density often indicates a greater presence of these structural features, which can enhance sub-surface flow. Higher lineament density is typically more favorable for recharge and storage, as these features can act as conduits for water to infiltrate and accumulate. Lineaments are linear or curved features controlled structurally, and their comparatively straight alignments in satellite images facilitate their identification. Using an automated technique, lines of the research region are extracted from satellite imageries. Next, the LD map was created using the Arc-GIS as shown in Fig. 6. Based on the closeness of lineaments, ranks are assigned for lineament density. It is found that when a location becomes more remote from the lineaments, potency of groundwater potential decreases. The Rose diagram of the Gomati District, Tripura is shown in Fig. 7.

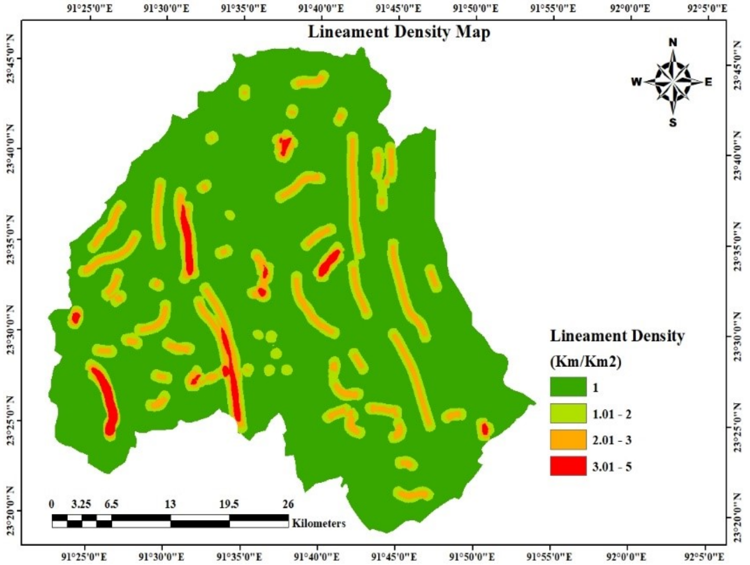

Figure 6: Lineament Density of the Gomati District, Tripura

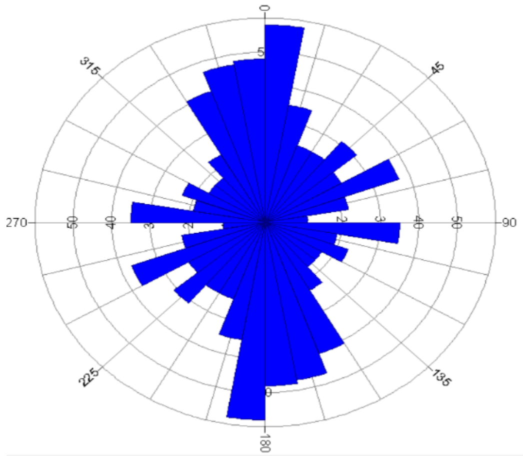

Figure 7: Rose diagram of the Gomati District, Tripura

Geology (G)

Geology is fundamental in determining groundwater potential as it influences the critical characteristics of rocks that affect water movement and storage (Verma et al., 2022). The composition, structure, and properties of geological formations, such as porosity and permeability, determine how much water rocks can hold and how easily water can flow through them. Areas with rocks that have high porosity and permeability are more likely to have greater groundwater storage capacity and more efficient water movement.

Additionally, geological formations can impact seepage capacity and capillary pressure, which are crucial for understanding groundwater recharge and discharge dynamics. By analyzing geological factors, it becomes possible to identify regions with favorable conditions for groundwater resources and effectively manage water supply and conservation. Geology shapes key petro-physical properties like rock composition, seepage capacity, and capillary pressure, which are crucial for groundwater movement. Rocks with high porosity and permeability can store more groundwater. By digitizing the shape file of geological map, the geology map was produced (Fig. 8). The classification helps understand their impact on groundwater behavior. In Gomati District, mainly three types of geological formations have been found as shown in Fig. 8.

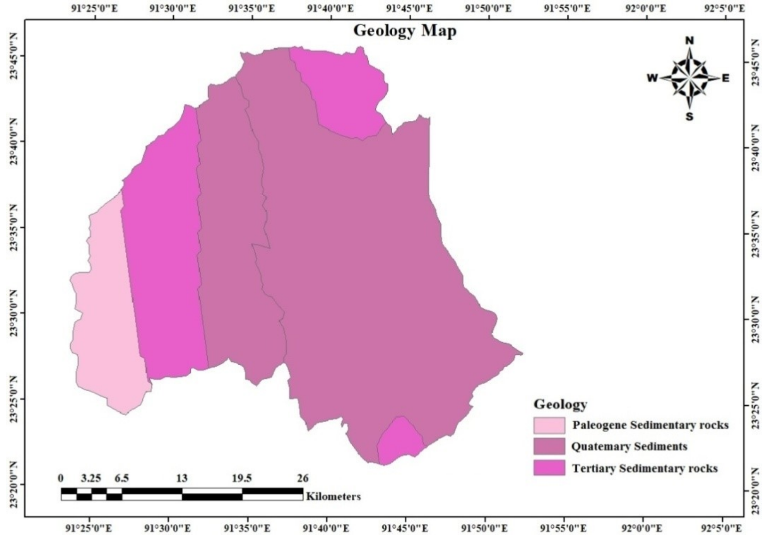

Figure 8: Geology Map of the Gomati District, Tripura

Rainfall (R)

Zones with less rainfall might not be beneficial for groundwater recharge (Verma et al., 2024). Annual rainfall data from the research area's rain gauges were sourced from the IMD, Guwahati. There are four types of rainfall zones on the rainfall map, each with 250 mm spacing. As per the rainfall map, higher altitude areas are given more annual rainfall than regions with lower elevations. There may be variations in rainfall between regions. This is where the annual precipitation information for the last 33 years comes from the rain gauge stations, and the amount of rainfall that has appeared in the research region is determined using the IDW interpolation method. Subsequently, each zone is given a weight and classified at equal intervals. Four groupings have been established: low (238-244 mm), moderate (245-250 mm), high (251-256 mm), and extremely high (257-262 mm) based on the maximum and minimum rainfall (Fig. 9).

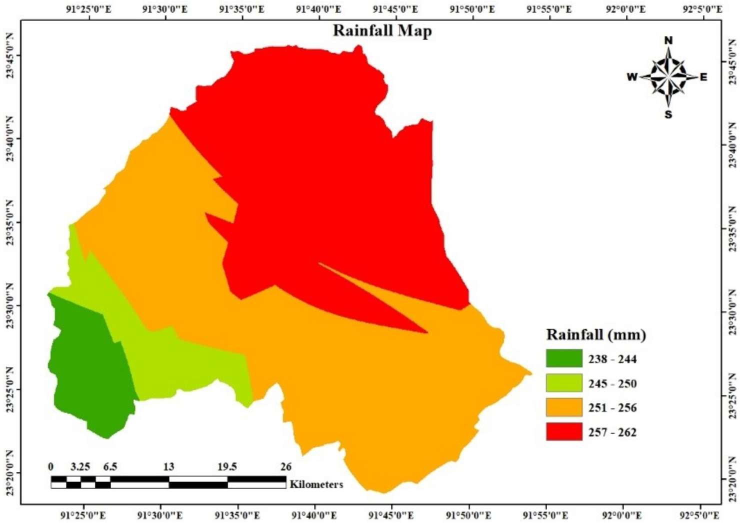

Figure 9: Rainfall Map of the Gomati District, Tripura

Soil Type (ST)

Soil type is crucial in determining groundwater potential because it directly influences water infiltration, retention, and movement within the subsurface (Verma et al., 2022). High-permeability soils like sand and loam enhance groundwater recharge, while low-permeability soils like clay and silt limit it by retaining surface water. Soil texture and structure affect water movement, influencing groundwater depth and availability. By understanding soil types and their properties, it is possible to better assess and manage groundwater resources, ensuring effective recharge and sustainable water supply. The primary determinant of the region's ability to absorb infiltration is its soil. The two main soil types in the region are sandy loam and loamy soil, as shown in Fig. 10. The permeability of loamy soil is mild to moderate, while that of sandy loam is very high.

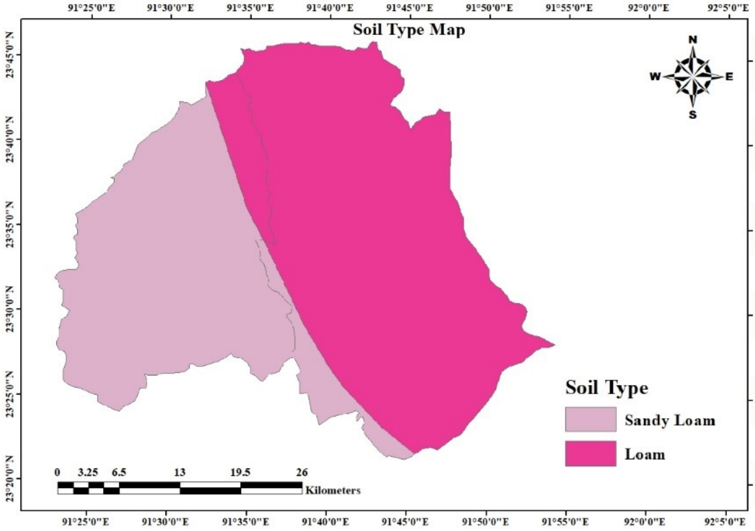

Figure 10: Soil Type Map of the Gomati District, Tripura

The groundwater potential map

Groundwater availability was assessed using the final normalized thematic layer weights, along with each layer's constituent features. Figure 11 visually represents the spatial distribution of groundwater potential across the district, categorized into excellent, good, fair, and poor zones. The area distribution is as follows: excellent (3%), good (81%), fair (16%), and poor (0%). The findings reveal that the majority of the Gomati district, especially within the Gomati River basin, falls under the good groundwater potential zone, covering 261.5673 km² (81% of the total area). The fair potential zone occupies approximately 53.34002 km² (16%), while the excellent zone spans about 9.045782 km² (3%). Notably, there are no areas classified as poor, indicating that the region generally has favourable groundwater availability.

The distribution of these potential zones is summarized in Table 7, which provides a clear breakdown of the areas and their corresponding percentages. This table summarizes the spatial extent and proportion of each groundwater potential zone in the study area. Table 8 further details the classification of thematic layers influencing groundwater availability, including factors such as lineament density (LD), geology (G), rainfall (R), slope (S), drainage density (DD), land use/land cover (LU/LC), and soil texture (ST). Each thematic feature is assigned a grade, ranking, and weightage based on its contribution to groundwater potential. This table provides a detailed breakdown of the factors influencing groundwater potential, their classification, and their assigned weightage based on their impact.

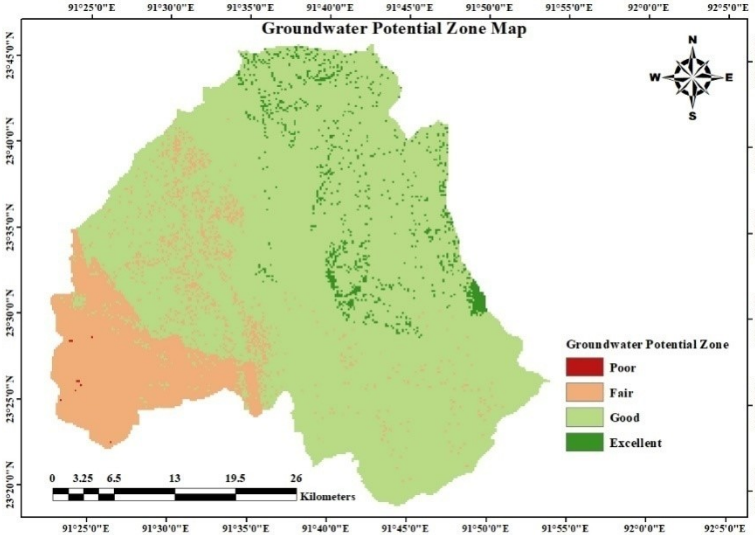

Figure 11: Potential Groundwater Zones in the Gomati District

Table 7: Total area and its percentage where groundwater may be present

Potential Groundwater zone	Area (km^2)	Percentage %
Poor	0.071289	0
Fair	53.34002	16
Good	261.5673	81
Excellent	9.045782	3

Table 8: Classification of the elements that impact the groundwater availability

Control features	Groups	Grade	Ranking	Weightage (%)
LD	1	2	Poor	5.10
	1.01-2	3	Moderate	
	2.01-3	4	Good	
	3.01-5	5	Excellent	
G	Loamy Sand	5	Excellent	24.33
	Sandy Clay Loam	4	Good	
R	238-244	2	Poor	37.31
	245-250	3	Moderate	
	251-256	4	Good	
	257-262	5	Excellent	
S	1	5	Excellent	13.54
	1.01-2	4	Good	
	2.01-3	3	Moderate	

	3.01-55	2	Poor	
DD	1	5	Excellent	9.08
	1.01-2	4	Good	
	2.01-3	3	Moderate	
	3.01-5	2	Poor	
LU/LC	Built up Areas	2	Poor	6.85
	Water Body	3	Moderate	
	Forest and Vegetation	4	Good	
	Farmland	5	Excellent	
ST	Sandy Loam	5	Excellent	3.74
	Loam	4	Good	

Discussion

The zoning of groundwater potential areas provides crucial information that can significantly aid in addressing groundwater-related challenges in the Gomati District. By identifying areas with excellent, good, and fair groundwater potential, this study enables targeted interventions for sustainable groundwater management. Specifically, the zoning map allows for the prioritization of high-potential zones for water extraction, while fair zones can be monitored and improved through recharge efforts such as rainwater harvesting or artificial recharge. Moreover, the zoning helps policymakers and local authorities plan infrastructure and agricultural activities more efficiently, ensuring that groundwater resources are utilized sustainably. It can also inform decisions on where to focus future drilling activities, reducing the risk of failed boreholes and minimizing costs. Overall, this zoning provides a strategic tool to manage and mitigate groundwater scarcity issues while promoting long-term water security in the region.

The study reveals that drainage density significantly affects groundwater availability, with higher densities (3.01-5 km/km^2) corresponding to excellent groundwater prospects. This result aligns with similar studies conducted in parts of Africa and South Asia, where lower drainage densities have also been linked to enhanced groundwater recharge due to increased infiltration rates (Lacombe et al., 2017;Meng et al., 2024). The LU/LC map, combined with NDVI analysis, indicates that dense vegetation and cropland support higher groundwater recharge. This is consistent with studies in semi-arid regions of India (Anusha et al., 2022), which found that bare and agricultural land enhances recharge, while forested areas, despite higher rainfall, may not contribute as effectively to groundwater reserves due to surface runoff. The study's slope classification confirms that flatter terrains promote better groundwater recharge, as steep slopes lead to faster surface runoff. This finding is corroborated by studies conducted in regions with similar topography, such as the Himalayan foothills where flatter slopes were also deemed critical for recharge (Dass et al., 2021). Rainfall distribution plays a significant role in determining groundwater potential, with higher rainfall regions showing increased groundwater prospects (Kumar et al., 2023). Similar trends have been observed in studies from the Middle East and Southeast Asia where spatial rainfall variability was found to be a primary factor in groundwater distribution (Wu et al., 2020).

CONCLUSION

The present study demonstrates a thorough investigation of the key influencing factors of groundwater and integrates GIS, RS, and AHP to classify various possible zones for the groundwater availability in the Gomati District, Tripura. The conclusions drawn from the study are summarized as below:

1. The study reveals that drainage density significantly influences groundwater availability. The Gomati River Basin is derived from the Debtamura hill range. Therefore, lower drainage densities correspond to higher groundwater potential due to increased infiltration. Drainage density was categorized into four classes, with extremely high groundwater prospects associated with the densest drainage networks (3.01-5 km/km^2) and very low prospects with the least dense networks (0-1 km/km^2).

2. The LU/LC map highlights groundwater recharge patterns. NDVI values show that dense vegetation (values above 0.4) enhances infiltration and recharge, while bare ground (values below 0.15) also supports recharge. Dense forests with high rainfall are less effective for recharge. Therefore, prioritizing cropland and barren land for groundwater recharge is recommended due to their higher infiltration potential.

3. Slope analysis reveals that flatter terrains are more favourable for recharge due to increased water accumulation. Steeper slopes, on the other hand, result in reduced groundwater recharge as precipitation quickly runs off. The study classified slope values into four categories: flat (1%), moderate (1.01-2%), medium (2.01-3%), and steep (3.01-55%). Flatter and moderate slopes are assigned higher weight due to their better recharge potential, while steeper slopes receive lower weight.

4. The study used rainfall data from the IMD, categorizing rainfall into four groupings: low (238-244 mm), moderate (245-250 mm), high (251-256 mm), and extremely high (257-262 mm) based on the maximum and minimum rainfall. The spatial rainfall distribution map was created using IDW interpolation. Higher altitude areas receive more rainfall, enhancing groundwater potential, while regions with less rainfall are less favourable.

5. The groundwater potential zones were mapped using the Arc-GIS, resulting in four categories: excellent (3%), good (81%), fair (16%), and poor (0%). The analysis revealed that most of the Gomati district and Gomati River basin exhibit excellent groundwater potential, with the good zone covering 81% (261.57 km^2) of the area. The fair zone covers 16% (53.34 km^2), and the excellent zone covers 3% (9.05 km^2). No areas were classified as poor, indicating generally favourable groundwater conditions.

6. This study, the first of its kind in Gomati District, Tripura, identifies district with good groundwater potential. The high-resolution map highlights drainage density and slope as crucial factors, providing a valuable resource for sustainable water management and planning. This detailed framework aids policymakers in prioritizing areas for groundwater development and conservation, offering a replicable model for similar terrains.

7. A limitation of the present study is that the analysis is based on static data which does not account for temporal changes. Additionally, the study's accuracy is constrained by the resolution of satellite data, and potential errors introduced during raster conversion.

8. Future studies should consider incorporating additional parameters, such as soil moisture, lithology, and geomorphology, to further enhance groundwater assessments. Temporal studies capturing seasonal and annual variations could offer more dynamic insights into groundwater potential. Employing advanced analytical techniques, including machine learning models, may also refine the predictions. Expanding this research to other regions could provide a broader understanding of groundwater resources and offer more robust solutions for water management.

Declaration of competing interest

The authors declare that they have no know competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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