# A Multi-criterian Approach to Identify Groundwater Potential Zones in the Subarnarekha River Basin Using Integrated Analytical Hierarchy Process and Geospatial Technology

## Rupa Sharma [a], Rahul Kumar Pandey [a*] and Abhay Krishna Singh [a]

[a] *Department of Geography, Dr. Shyama Prasad Mukherjee University, Ranchi-834008, Jharkhand, India.*

*Authors' contributions*

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## ABSTRACT

The intense extraction of groundwater and changing climate patterns have strained global groundwater supplies. As the demand for drinkable water rises worldwide, assessing groundwater availability and aquifer output becomes increasingly important. Geographic information systems (GIS) are being used more frequently for groundwater exploration due to their speed and provision of preliminary data. This study focuses on mapping groundwater availability in a minor tropical river basin in India, using a combination of GIS and the analytical hierarchy process (AHP). Ten thematic

layers were generated and analyzed, including Geology, Geomorphology, Land use and land cover (LULC), Lineament density, Drainage density, Rainfall, Soil type, Slope, Topographic Wetness Index ( TWI), and curvature to delineate groundwater potential zones. AHP was employed to assign weights to each category based on their water retention properties. The resulting map was validated against existing groundwater data, demonstrating an accuracy of approximately 85%. The groundwater potential zones were classified as high, moderate, and, low. The moderate potential zone covered 59% of the basin, while the low and high potential zones constituted 29% and 11% respectively. High and low potential regions were limited to small sections of the basin. In conclusion, this research successfully mapped the groundwater availability in the Rarhu River watershed using GIS and AHP. The findings highlight the distribution of different groundwater potential zones, providing valuable information for sustainable water resource management in the area.

## 1. INTRODUCTION

Water is the foundation of ecosystems and the essential ingredient for life itself. In addition to being essential to human life, water is also a priceless gift for all plants, animals, and other living things [1]. This priceless resource kindly supplies about 34% of the freshwater needed to support human civilization worldwide [2,3,4]. In India, 50% of the urban and 90% of the rural populations get their domestic water from groundwater. In addition, the agricultural sector uses around 70% of the groundwater for irrigation [5]. There are two main sources of water: sub-surface water, also called groundwater, which appears as springs, wells, infiltration wells, and galleries, and surface water, which includes rainwater, river water, lake water, and ocean. Because of its chemical content, constancy in temperature, purity, and reduced contamination susceptibility, groundwater is vital to towns, industry, and agriculture worldwide. Numerous natural and man-made variables influence the distribution and availability of groundwater, with tropical and subtropical areas experiencing major issues due to high population density and economic activity. According to the National Institution for Transforming India (NITI) Aayog, the lack of freshwater availability in India puts about 0.6 million people under high to extreme water stress. The seriousness of the problem is further demonstrated by the fact that 75% of Indian households do not have access to clean water on their property. The World Bank has issued a concerning report indicating that without immediate action, India will confront a severe water crisis in the upcoming decades. It's projected that by 2025, the nation will experience water stress, with the possibility of becoming a water-scarce region by 2050 [6]. Groundwater, presently contributing 34% to India's annual water supply, demands meticulous management to stave off this impending crisis. Fortunately, the utilization of geographic information systems (GIS) and remote sensing technologies present robust solutions for the monitoring and management of this essential natural resource [2,7]. Traditional methods for identifying and mapping regions with substantial groundwater potential heavily rely on comprehensive ground surveys utilizing geophysical, geological, and hydrogeological techniques. However, these approaches tend to be costly and time-intensive [8,9,10]. Conversely, geospatial instruments present a swifter and more economical approach to generating and simulating crucial data across diverse geoscience fields. These instruments offer an efficient substitute for evaluating zones of groundwater potential [11,12,13,14].

A review of existing literature demonstrates the diverse array of methods researchers have employed to identify and map groundwater potential zones. These techniques include probabilistic models like Shannon's entropy, decision trees, artificial neural networks, weights-of-evidence, logistic regression, evidential belief function, certainty factor, and frequency ratio. They also include machine learning techniques like random forest and maximum entropy modelling [15,16,17,18,19,20,21,22,23,24,25]. Notably, remote sensing and geographic information systems (GIS) emerge as particularly potent tools for swiftly estimating the potential and distribution of natural resources. The integration of these geospatial technologies offers an efficient approach to assessing groundwater resources across extensive areas before conducting costly surveys [26,27,28].

In this investigation, a combined strategy was utilized, integrating the MCDM, Analytical Hierarchy Process (AHP), and, Geospatial techniques, toward outline groundwater potential mapping. AHP, introduced by Tomas Saaty in [29], proves invaluable for tackling intricate decision-making in groundwater-related domains. This methodology simplifies complex decisions by conducting pairwise comparisons and then consolidating the findings. Moreover, AHP incorporates a feature designed to evaluate outcome consistency, hence mitigating decision-making bias. Through a fusion of AHP and GIS capabilities, this approach offers a robust method for mapping and evaluating regions with substantial groundwater potential [29]. The study centered on the Rarhu watershed, a small tributary of the Subarnarekha River originating in the northeastern part of the Ranchi plateau. The Rarhu River, draining this northeastern plateau region, serves as a crucial lifeline for a large population heavily reliant on agriculture. Groundwater supplies are vital to the communities in this area for household, agricultural, and horticultural uses.

The foremost aim of this research was to demarcate, classify, and mapping of the groundwater potential zones within the Rarhu watershed. The goal of this project was to present a case study that may serve as a model for the development of sustainable water resources and regional planning techniques. By accurately assessing and mapping areas with high groundwater potential, the findings can guide efforts toward prudent management and utilization of this vital resource, thereby bolstering water security and sustaining the livelihoods of the local populace.

## 1.1 Study Area

The study zone encompasses the Rarhu watershed, a significant right-bank tributary within the Subarnarekha River system. Positioned in the eastern part of peninsular India, it lies southeast of the Chotanagpur plateau within the Ranchi district of Jharkhand state. Covering an area of roughly 600.53 km$^2$ in the drainage basin of Subarnarekha, the Rarhu watershed spans latitudes 23°27'6.962" N to 23°12'56.651" N and longitudes 85°23'11.79" E to 85°51'37.613" E (Fig. 1). The highest elevation reaches 777 meters above mean sea level. Originating from Baram village in the Namkum community development block of Ranchi district, the Rarhu River stretches approximately 56.11

km$^2$ merging with the Subarnarekha River near Shyam Nagar in the Birdidih area of West Bengal at an elevation of 152 meters (Fig. 2). This watershed serves as a significant case study area for evaluating groundwater potential and formulating sustainable water resource management strategies for the region.

## 2. MATERIALS AND METHODS

To identify groundwater potential zones within the Rarhu watershed, this study used geospatial techniques. Following a comprehensive review of global and regional literature, ten thematic layers were selected for identifying groundwater potential zones (Table 1). Ten thematic data layers encompassing the region's geology, geomorphology, land use/land cover (LULC), drainage density, lineaments, rainfall, soil, slope, curvature, and topographic wetness index were integrated using a knowledge-based factor analysis technique (Table 2). Remote sensing data preprocessing for the Rarhu watershed was conducted using ERDAS Imagine 2015 image processing software. Geographic Information System (GIS) techniques were applied using ArcGIS 10.7.1. Topographic map sheets at a 1:50,000 scale from the Survey of India (SOI 73E/11, 73E/15, 73E/16) were employed to delineate the watershed boundary and calculate drainage density and lineament density. Sentinel 2A satellite imagery with a spatial resolution of 10m, specifically a geo-coded false-color composite (FCC), was utilized to generate LULC thematic layers within the GIS framework [2].

The amalgamation of various geospatial datasets and analytical methodologies empowered researchers to systematically assess and map areas demonstrating high groundwater potential within the Rarhu watershed. Existing maps illustrating the geology, geomorphology, and soil attributes of the region were sourced from the Bhukosh and FOA soil portals, digitized, and tailored to fit the study area boundaries. Terrain parameters such as slope, curvature, and topographic wetness index (TWI) were extracted from high-resolution digital elevation model ALOS PALSAR (12.5m) data [7,30].

Rainfall data for the area was retrieved from the IMD Pune data portal. Using the inverse distance weighting (IDW) interpolation method, a geographical distribution map of the watershed's rainfall patterns was created [31,32]. Through the synthesis of this diverse array of geospatial data layers about various environmental factors, the researchers conducted a comprehensive

analysis to delineate zones showcasing promising groundwater potential within the Rarhu watershed.

## 2.1 Multi-criteria Decision Analysis (MCDA) using GIS Techniques

One well-known GIS-based multi-criteria decision analysis technique for defining groundwater potential zones is the Analytical Hierarchical Process (AHP). There are several benefits to using the Analytical Hierarchy Process (AHP) to identify groundwater potential zones. It offers a methodical framework for decision-making that is structured and enables the weighting of various criteria according to their relative relevance. AHP efficiently combines many data sources and aspects, guaranteeing an all-encompassing evaluation. Because of its adaptability to various geographies and consistency checks that reduce biases, it produces assessments of groundwater potential that are more reliable than those obtained with other techniques. This technique facilitates the amalgamation of various thematic data layers that influence the occurrence and movement of groundwater. In this study, a total of 10 distinct thematic layers were assessed, representing factors governing water flow and storage within the area of interest. The significance and interrelationship of these influencing factors were quantified through assigned weights, reflecting their expected contributions to groundwater occurrence and expert judgment. Parameters with greater weights indicate a more significant impact on groundwater potential, while those with lower weights suggest a lesser influence. The precise weights allocated to every characteristic were ascertained by using Saaty's basic relative importance scale, which spans from 1 to 9. The researchers' expertise in the field of study and a thorough analysis of earlier, pertinent studies served as the foundation for this weight-assigning process.
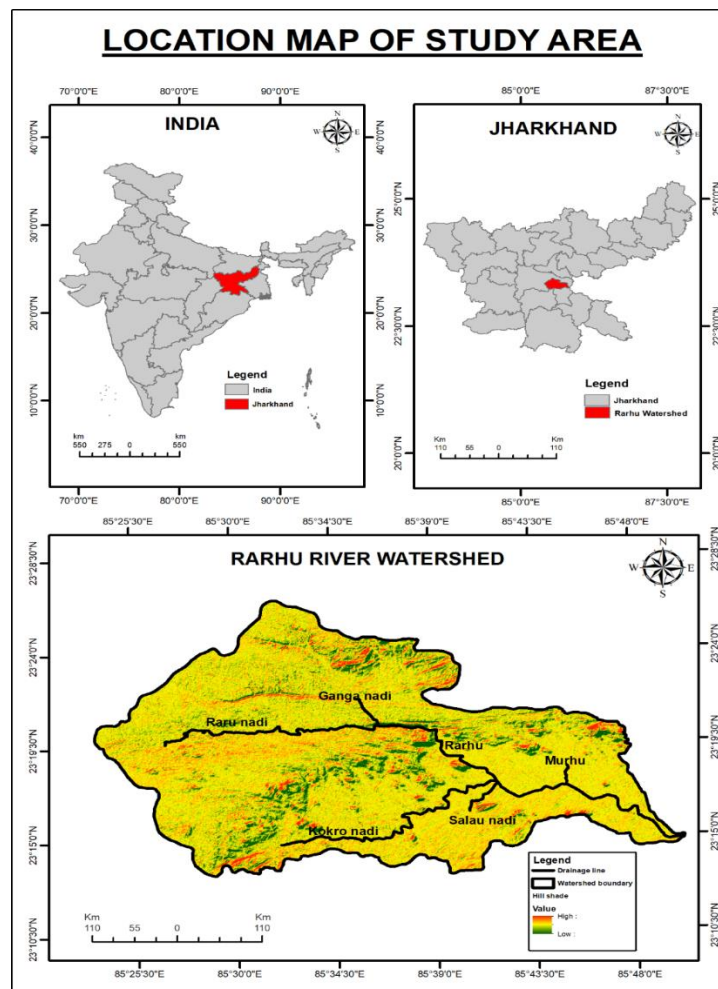


**Fig. 1. Showing the location map of the study area**

**Table 1. A literature overview of various parameters employed in global and regional studies for delineating groundwater potential zones utilizing the Analytical Hierarchy Process (AHP) method**

| S. N | Study Area | G | GM | LULC | LD | DD | SL | S | RF | TWI | CUR | E | TRI | Literature |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Uttarakhand, India | √ | √ | √ | - | √ | √ | √ | √ | √ | √ | - | - | Singh et al. [44] |
| 2 | Jhargram, West Bengal | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | Guria et al. [45] |
| 3 | Domah (M.P) | - | √ | √ | √ | √ | √ | √ | - | √ | - | - | √ | Moharir et al. [46] |
| 4 | Coimbatore, South India | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | - | - | Kom et al., 2022 |
| 5 | Anantapur (A.P) | √ | √ | √ | √ | √ | √ | √ | √ | - | - | - | - | Rajasekhar et al. [47] |
| 6 | Nasarawa State, Nigeria | √ | √ | √ | √ | √ | √ | √ | √ | - | - | - | - | Ifediegwu [48] |
| 7 | Kashmir valley | - | √ | √ | √ | √ | √ | √ | √ | - | - | - | - | Dar et al. [49] |
| 8 | Gautham Buddh Nagar (U.P) | √ | √ | √ | - | √ | √ | √ | - | - | - | - | - | Banerjee et al. [50] |
| 9 | Karha (Maharashtra) | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | - | - | Bera et al. [51] |
| 10 | Southern Western Ghats | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | - | - | Arulbalaji et al. [52] |
| 11 | Dumka (Jharkhand) | - | √ | √ | √ | √ | √ | √ | √ | - | - | - | - | Murmu et al. [4] |
| 12 | Tehran (Iran) | √ | - | √ | √ | √ | √ | √ | √ | - | - | - | - | Panahi et al. [53] |
| 13 | Unnao (U.P) | √ | √ | √ | √ | √ | √ | √ | √ | - | - | - | - | Agarwal et al. [54] |
| Current Study | Rarhu watershed, Jharkhand | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | - | - | |

**Table 2. This section elucidates the diverse datasets utilized in the study, detailing their respective sources and applications in generating thematic layers for the delineation of groundwater potential zones**

| Types of Data | Scale/Resolution | Parameter | Sources Data |
|---|---|---|---|
| ALOS DEM | 12.5 m | Slope, Elevation, and, curvature | Earth Data (https://search.asf.alaska.edu/) |
| Topographical maps | 1: 50000 RF | Drainage density and, lineament density map | Onlinemaps Portal (https://onlinemaps.surveyofindia.gov.in/) |
| Geological and Geomorphological | 2M | Geology and Geomorphology map | Bhukosh (https://bhukosh.gsi.gov.in) |
| Rainfall data | 0.25*0.25 degree | 30 years average (1992 - 2022) | IMD (https://www.imdpune.gov.in) |
| Soil data | 1: 1250000 | Soil texture map | FAO Soils Portal (https://www.fao.org/soils-portal) |
| Sentinel 2A | 10 m | LULC | ESRI Land Cover (https://livingatlas.arcgis.com/landcover/) |
| Groundwater | Well depth | Method Validation | CGWB 2022 (https://cgwb.gov.in/cgwbpnm/public/uploads/documents/16883646811420506028file.pdf) |

**Table 3. Pairwise comparison matrix incorporating the relative importance weights assigned to the ten thematic layers employed in the present study**

| Parameters | RF | LULC | GM | G | S | DD | SL | LD | CUR | TWI |
|---|---|---|---|---|---|---|---|---|---|---|
| RF | 1 | 1/3 | 1 | 1/5 | 1 | 1 | 1/3 | 1 | 1/3 | 1/3 |
| LULC | 3 | 1 | 3 | 1/3 | 1 | 1 | 1 | 1 | 1/3 | 1 |
| GM | 1 | 1/3 | 1 | 1/3 | 1 | 1 | 1/3 | 1 | 1/5 | 1/3 |
| G | 5 | 3 | 3 | 1 | 1 | 3 | 3 | 1 | 1 | 3 |
| S | 1 | 1 | 1 | 1 | 1 | 3 | 1 | 1 | 1/5 | 1 |
| DD | 1 | 1 | 1 | 1/3 | 1/3 | 1 | 1 | 5 | 1 | 1 |
| SL | 3 | 1 | 3 | 1/3 | 1 | 1 | 1 | 1 | 1/3 | 1 |
| LD | 1 | 1 | 1 | 1 | 1 | 1/5 | 1 | 1 | 1/3 | 1 |
| CUR | 3 | 3 | 5 | 1 | 5 | 1 | 3 | 3 | 1 | 3 |
| TWI | 3 | 1 | 3 | 1/3 | 1 | 1 | 1 | 1 | 1/3 | 1 |
| Sum | 22.00 | 12.67 | 22.00 | 5.87 | 13.33 | 13.20 | 12.67 | 16.00 | 5.07 | 12.67 |

By combining the ten weighted theme layers via the AHP multi-criteria analysis framework, the researchers synthesized diverse spatial data to delineate areas demonstrating relatively higher potential for groundwater resources. A value of 9 indicates extreme importance, 8 indicates very strong importance, 7 indicates very strong to extreme importance, 6 indicates strong plus importance, 5 indicates strong importance, 4 reflects moderate plus importance, 3 indicates moderate importance, 2 indicates weak importance, and 1 indicates equal importance. Saaty's basic scale of relative importance provides a quantitative framework for allocating weights. The thematic layers were given weights according to their prospective water-holding capacity and perceived value using this classification.

To determine these weights, pairwise comparisons were conducted for all thematic layers, resulting in a comparison matrix (Table 3). After the initial pairwise comparison of thematic layers, the judgment matrix underwent normalization. Next, the consistency index (CI) and the random consistency index (RI) were calculated. The principal eigenvalue (λmax) was derived, enabling the computation of the consistency ratio (CR). The final weights allocated to each thematic layer were determined based on the CR value less the 0.1, which evaluates the consistency of pairwise judgments throughout the Analytical Hierarchy Process (Table 4). Within the GIS platform, the sub-classes of each thematic layer underwent reclassification using the natural breaks classification method. These sub-classes were then ranked on a scale from 0 to 9, representing their relative influence on groundwater development and occurrence. This systematic approach, grounded in Saaty's relative importance scale and the pairwise comparison of thematic layers, enabled researchers to objectively quantify the relative contributions of each data layer to the delineation of groundwater potential zones [30]. The allocated ranks and weights for each of the thematic layers taken into account during the analysis are shown in Table 5. The consistency ratio (CR) was determined using the following procedures to assess the consistency of these weight assignments: (1) The eigenvector method was used to obtain the major eigenvalue (λ), as indicated in Table 3, and (2) equation (1) below was used to get the Consistency Index (CI).

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

In this case, n stands for the total number of factors used in the analysis. CR=CI/RI is the definition of the consistency ratio, where RI stands for the Random Consistency Index value. Saaty's standard reference provided these RI values (Table 6). Saaty 1990 [29] states that the analysis can continue if the Consistency Ratio (CR) is 0.10 or less. A CR greater than 0.10 suggests that judgments need to be reevaluated to find and address sources of discrepancy. In pairwise comparisons, a CR score of 0 denotes perfect consistency. The threshold value shows adequate consistency in the judgment matrix, as it is not much greater than 0.1. Equation (2) was utilized to integrate all ten thematic layers through the weighted overlay analysis approach within a GIS platform to create the groundwater potential zone map of the Rarhu watershed.
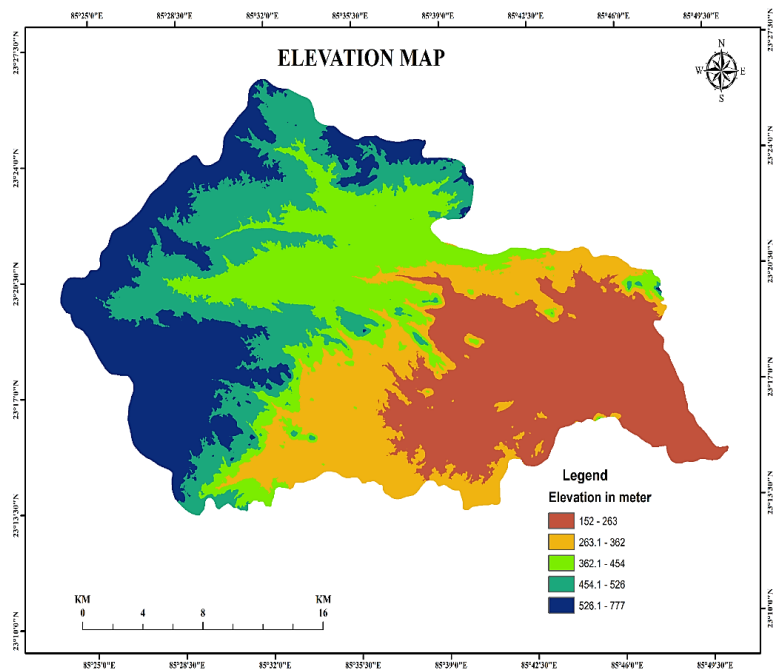
$$GWPZ = \sum_{i}^{n} (x_A \times y_B) \qquad (2)$$

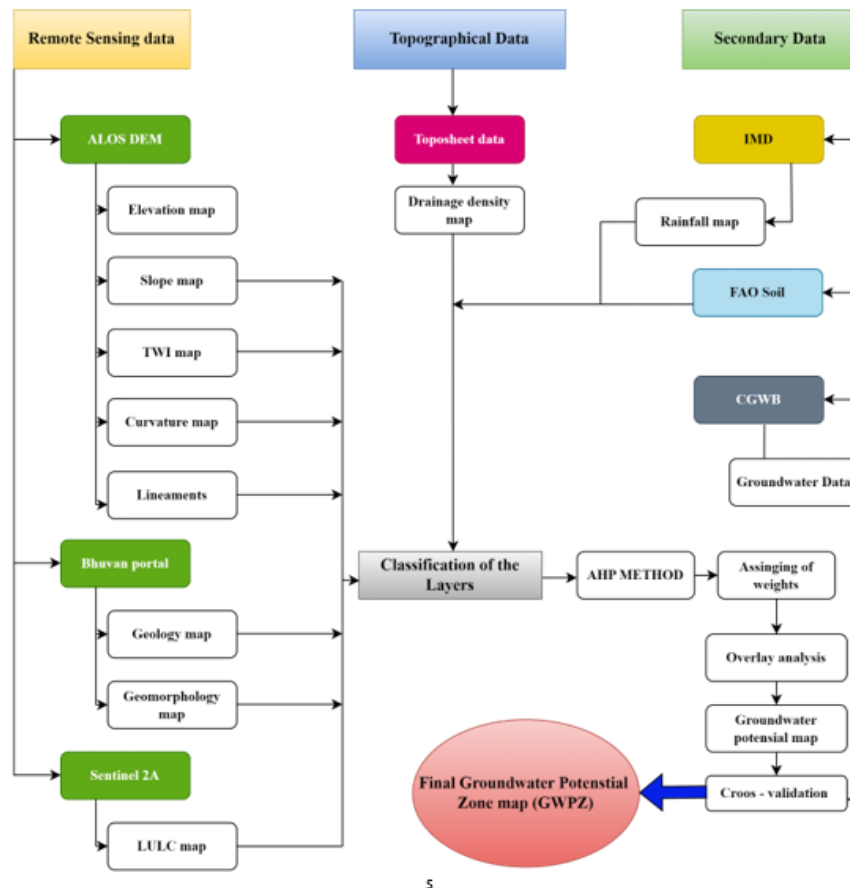**Fig. 2. Showing the elevation map of the study area**



**Fig. 3. Schematic flowchart illustrating the methodological framework employed for the delineation and mapping of Groundwater Potential Zones**

**Table 4. Normalized pairwise comparison matrix and the corresponding weights assigned to each parameter influencing the distribution of groundwater potential in the present study**

| Parameters | RF | LULC | GM | G | S | DD | SL | LD | CUR | TWI | Lamda max | CI | CR | NPE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RF | 1.00 | | | | | | | | | | | | | 0.160 |
| LULC | 0.33 | 1.00 | | | | | | | | | | | | 0.086 |
| GM | 0.20 | 0.33 | 1.00 | | | | | | | | | | | 0.047 |
| G | 0.33 | 1.00 | 3.00 | 1.00 | | | | | | | | | | 0.086 |
| S | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | | | | | | 11.135 | 1.49 | 0.085 | 0.097 |
| DD | 1.00 | 3.00 | 3.00 | 3.00 | 1.00 | 1.00 | | | | | | | | 0.158 |
| SL | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | | | | | | | 0.135 |
| LD | 1.00 | 1.00 | 3.00 | 1.00 | 3.00 | 1.00 | 0.20 | 1.00 | | | | | | 0.106 |
| CUR | 0.33 | 0.33 | 1.00 | 0.33 | 0.20 | 0.20 | 0.33 | 1.00 | 1.00 | | | | | 0.038 |
| TWI | 0.33 | 1.00 | 3.00 | 1.00 | 1.00 | 0.33 | 1.00 | 1.00 | 3.00 | 1.00 | | | | 0.086 |

**Table 5. Categorization of key factors influencing the spatial distribution of Groundwater Potential Zones in the present study**

| Parameters | Parameters class | Area (km²) | Area(%) | Rating | AHP weight |
|---|---|---|---|---|---|
| Rainfall | 1040.46 – 1089.48 | 57.15 | 9.52 | 1 | 0.160 |
| | 1089.49 – 1151.4 | 185.83 | 30.94 | 2 | |
| | 1151.41 – 1215.9 | 90.56 | 15.08 | 3 | |
| | 1215.91 – 1293.3 | 171.26 | 28.52 | 4 | |
| | 1293.31 – 1363.41 | 95.73 | 15.94 | 5 | |
| LULC | Deciduous broadleaf | 145.38 | 24.21 | 3 | 0.086 |
| | Crop land | 288.55 | 48.05 | 2 | |
| | Built up | 5.56 | 0.93 | 1 | |
| | Mixed forest | 59.99 | 9.99 | 3 | |
| | Shrub land | 65.40 | 10.89 | 2 | |
| | Barren land | 9.85 | 1.64 | 2 | |
| | Fallow land | 15.76 | 2.62 | 3 | |
| | Water bodies | 10.05 | 1.67 | 5 | |
| Geomorphology | Flood plain | 282.27 | 47.0 | 4 | 0.047 |
| | Moderately dissected hills | 3.7.75 | 51.25 | 2 | |
| | Pediment pediplain complex | 1.18 | 0.20 | 3 | |
| | Waterbodies other | 8.69 | 1.45 | 5 | |
| | Waterbody river | 0.64 | 0.11 | 5 | |
| Geology | Unclassified metamorphic | 2.85 | 0.47 | 5 | 0.086 |
| | Manbhum Granite | 9.22 | 1.54 | 1 | |
| | Chhotanagpur Gneissic complex | 588.46 | 97.99 | 3 | |
| Soil | Sandy clayloam | 398.99 | 66.44 | 5 | 0.097 |
| | Loam | 201.54 | 33.56 | 3 | |
| Drainage density | 0 -1.53 | 51.45 | 8.57 | 1 | 0.158 |
| | 1.54 – 2.17 | 143.40 | 23.88 | 2 | |
| | 2.18 – 2.72 | 202.36 | 33.70 | 3 | |
| | 2.73 – 3.4 | 160.76 | 26.77 | 4 | |
| | 3.41 – 5.26 | 42.57 | 7.09 | 5 | |
| Slope | 0 – 4.18 | 279 | 46.46 | 5 | 0.135 |
| | 4.19 – 8.37 | 197.20 | 32.84 | 4 | |
| | 8.38 – 14.64 | 77.61 | 12.92 | 3 | |
| | 14.65 – 23.79 | 33.37 | 5.56 | 2 | |
| | 23.8 – 66.67 | 13.35 | 2.22 | 1 | |
| Lineament density | 0 – 1,776.42 | 202.36 | 33.70 | 5 | 0.106 |
| | 1776.43-3,667.45 | 172.32 | 28.69 | 4 | |
| | 3667.46-5,959.61 | 119.17 | 19.84 | 3 | |
| | 5,959.62-8,824.8 | 73.36 | 12.22 | 2 | |
| | 8,824.81-14612.5 | 33.33 | 5.55 | 1 | |
| Curvature | -30.72- 2.11 | 23.69 | 3.95 | 1 | 0.038 |
| | -2.1 - -0.67 | 194.75 | 32.43 | 2 | |
| | -0.66- 0.56 | 275.76 | 45.92 | 3 | |
| | 0.57 – 2.41 | 102.94 | 17.14 | 4 | |
| | 2.42 – 21.76 | 3.39 | 0.56 | 5 | |
| TWI | 1.67 – 5.04 | 211 | 35.14 | 5 | 0.086 |
| | 5.05 – 6.72 | 267.22 | 44.50 | 4 | |
| | 6.73 – 9.06 | 84.69 | 14.10 | 3 | |
| | 9.07 – 12.35 | 29.51 | 4.91 | 2 | |
| | 12.36 – 20.32 | 8.11 | 1.35 | 1 | |

**Table 6. The random consistency index (RI) values corresponding to different matrix orders (n), as established by Saaty (1990)**

| No | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0.00 | 0.00 | 0.58 | 0.89 | 1.12 | 1.25 | 1.32 | 1.40 | 1.45 | 1.49 |

The weight of the theme layers is represented by X in the equation GWPZ=Groundwater Potential Zone, while the rank of the thematic layers' subclasses is indicated by Y. The thematic map is represented by the term A (A=1, 2, 3,... X), while the thematic map classes are represented by the term B (B=1, 2, 3,.. Y). A larger impact on groundwater potential zones is indicated by a factor with a higher weight value, whereas a smaller impact is suggested by a factor with a lower weight value. Three zones were identified on the final groundwater potential zone map: low, moderate, and high [31]. The information about groundwater prospects unique to the Rarhu watershed that was gathered for this study was then used to validate the final product. The flowchart of the approach used in this study is shown in Fig. 3.

## 3. RESULTS AND DISCUSSION

### 3.1 Geology

The geological configuration of an area significantly impacts the presence and distribution of groundwater resources [33]. The different geological formations in the research region were identified using the published geological map from the Geological Survey of India (GSI). The Rarhu watershed primarily comprises the Chhota Nagpur Gneissic Complex, encompassing 97.99% of the area, with minor occurrences of the Manbhum Granite (1.54%) and unclassified metamorphic rocks (0.47%) (Fig. 4). The predominant geological units in the study area consist of the Chhota Nagpur gneissic rocks and associated basic rocks [34]. During the weighted overlay analysis, a higher weight was assigned to the unclassified metamorphic rocks due to their potential for groundwater occurrence and storage. Conversely, a lower weight was allocated to the Chhota Nagpur Gneissic Complex, reflecting its comparatively lower groundwater prospectivity compared to the metamorphic units. By integrating geological data and assigning appropriate weights based on the hydrogeological characteristics of the rock formations, the researchers aimed to accurately depict the influence of geology on groundwater potential within the Rarhu watershed.

### 3.2 Geomorphology

Geomorphology, which is a representation of the topography and landform of a region, is one of the main variables that is widely used to define groundwater potential zones. It sheds light on the distribution of different landform characteristics and processes, including freezing and thawing, water flow, geochemical reactions, and temperature variations [30,35,36]. The study area exhibits a predominantly highland topographic character, characterized by mountainous and undulating terrain features. Approximately 98% of the region is comprised of flood plains and moderately dissected hills, with flood plains occupying 47% and dissected hills constituting 51.25% of the total area. The western and southwestern sectors of the study area are primarily dominated by hilly terrain. The Pediment Pediplain complex, somewhat divided hills and valleys, water rivers, floodplains, and other bodies of water are among the main geomorphic features. The upstream side of the watershed is predominantly characterized by moderately dissected hills and valleys, featuring sharp but rugged tops indicative of surface runoff affected by erosion. The Pediment Pedi plain complex is prevalent in the midland and lowland areas of the Rarhu watershed. Fig. 5 illustrates the geomorphology of the Rarhu watershed, with higher weight assigned to water bodies and lower weight given to lower moderately dissected hills and valleys.

### 3.3 Land Use and Land Cover (LULC)

Data on land use and land cover (LULC) is essential for understanding infiltration, soil moisture, surface water, groundwater, and groundwater demand. [33,37]. Many land use classifications, such as deciduous broadleaf forest, agriculture, built-up areas, mixed forest, shrubland, barren land, fallow ground, and water bodies, are noted within the Rarhu watershed (Fig. 6). The land use/land cover (LULC) classification analysis reveals that agricultural lands constitute the predominant land cover type, occupying 48% of the study area. Forested areas represent the second most extensive land cover class, covering 24.21% of the region's total extent. Among these, cropland dominates over

other categories. The high and midland regions primarily consist of deciduous broadleaf forest, mixed forest, and shrubland, while the lowlands are characterized by built-up areas, water bodies, barren land, shrubland, and fallow land. LULC classes such as forest and cropland significantly contribute to water retention compared to built-up areas, barren land, and fallow land [35]. Consequently, higher weight is assigned to deciduous forests, mixed forests, cropland, and water bodies, while lower weight is attributed to built-up areas, shrubland, barren land, and fallow land.
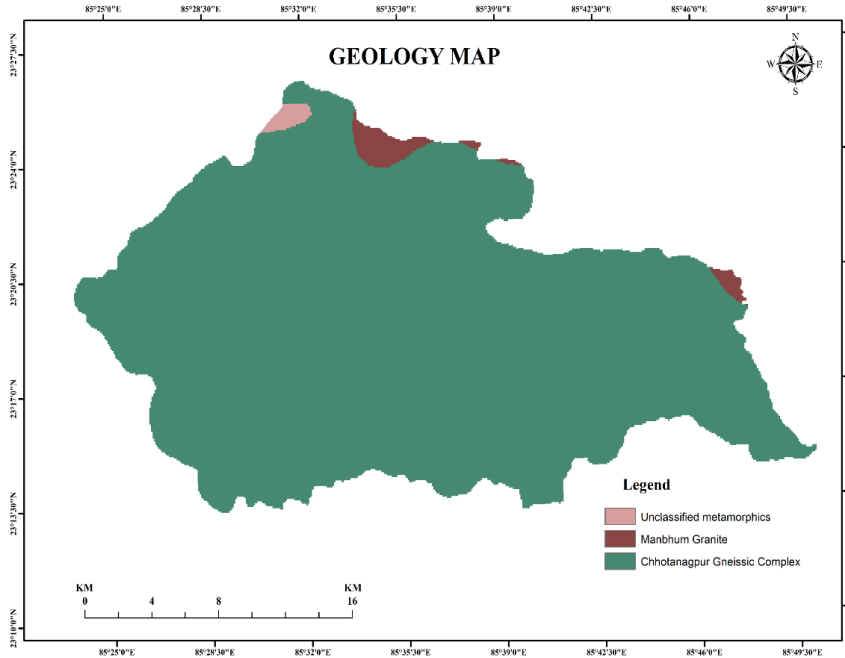


**Fig. 4. Showing the geology map of the study area**
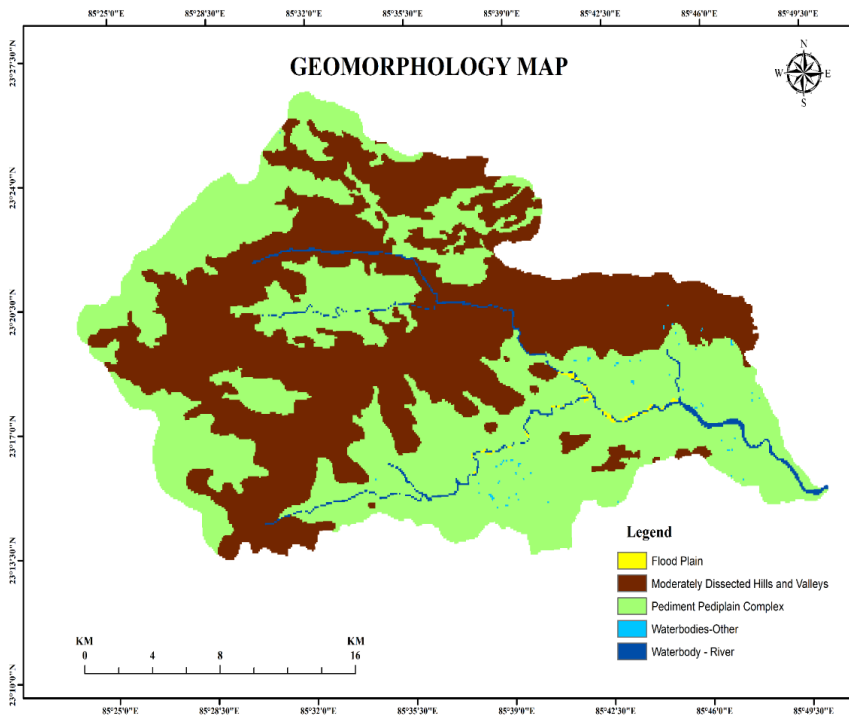


**Fig. 5. Showing the geomorphology map of the study area**
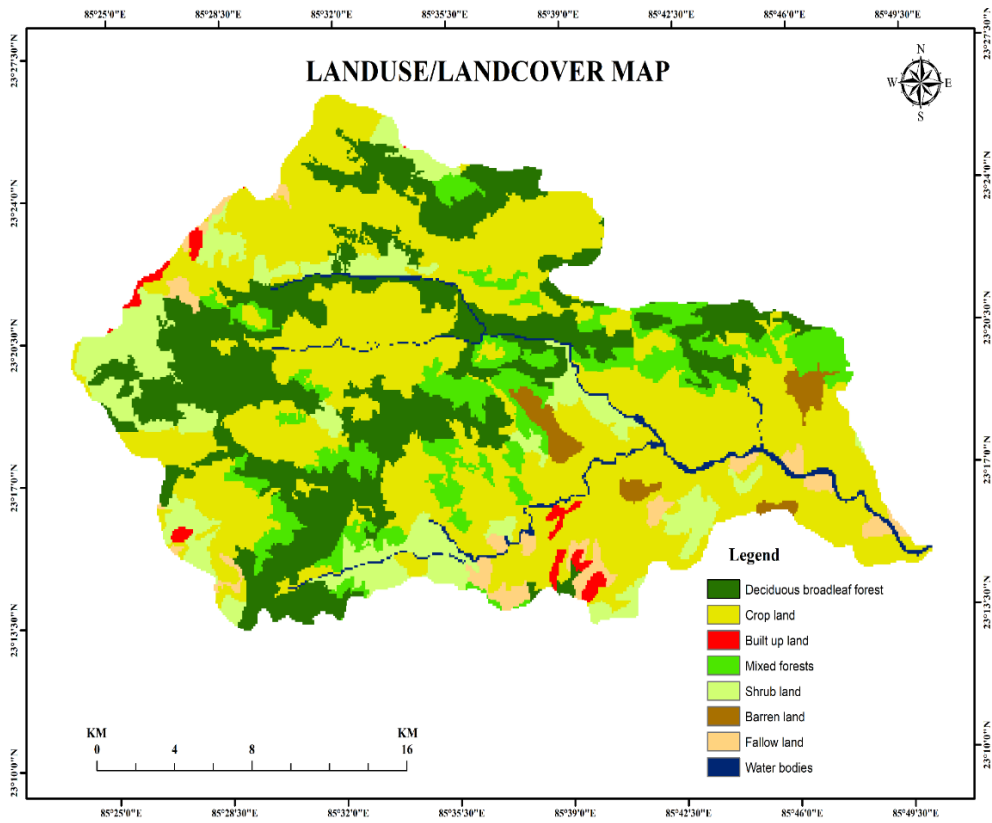
**Fig. 6. Showing the land use and land cover (LULC) map of the study area**
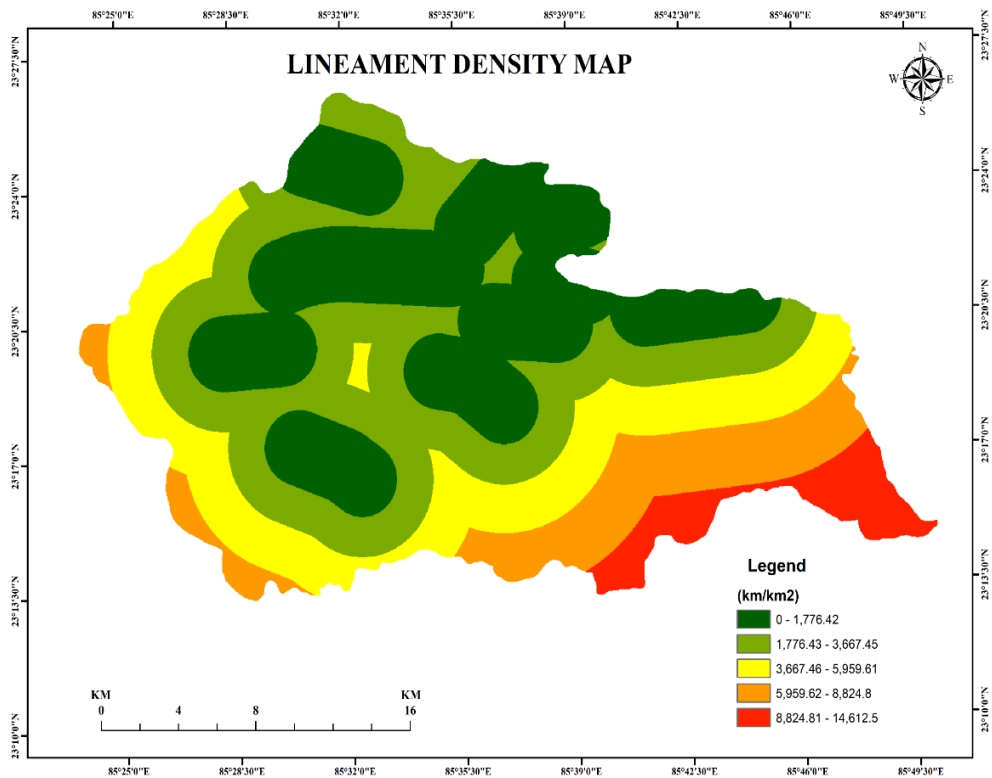


**Fig. 7. Showing the lineament density map of the study area**

## 3.4 Lineament Density

Geological structures govern the linear or curved characteristics known as lineaments. They represent areas where there is faulting and fracture, which increases secondary porosity and permeability [33]. Lineaments for the study area were acquired from the Bhukosh portal. Subsequently, a lineament density map was generated using GIS software, as shown in (Fig. 7). The results were then carefully examined and divided into five groups: Very Low (0–1,776.42 km/km$^2$), Low (1,776.43–3,667.45 km/km$^2$), Moderate (3,667.46–5,959.61 km/km$^2$), High (5,959.62–8,824.80 km/km$^2$), and Very High (8,824.81–14,612.5 km/km$^2$). Lineament density was ranked according to how close together the lineaments were. It has been shown that the strength of groundwater potential reduces with increasing separation from lineaments. Courses with a higher density are given more weight, whereas courses with a lower density are given less weight.

## 3.5 Drainage Density

Drainage density plays a critical role in groundwater availability and contamination [11]. It is an inverse function of permeability and a key parameter in delineating groundwater potential zones. The calculation of drainage density involves dividing the aggregate length of all streams within a drainage basin by the drainage basin's entire area [33]. Reduced infiltration is indicated by high drainage densities, which negatively affects an area's capacity for groundwater. On the other hand, low drainage density indicates high infiltration, which increases the possibility of groundwater. Reclassified, the drainage density was divided into five groups: Very High (3.41–5.26 km/km$^2$), High (2.73–3.40 km/km$^2$), Moderate (2.18–2.72 km/km$^2$), Low (1.54–2.17 km/km$^2$), and Very Low (0–1.53 km/km$^2$). Low density is given a higher weight in groundwater potential zonation, whereas high density is given a lesser weight. The drainage density map of the Rarhu watershed is seen in Fig. 8.

## 3.6 Slope

One important aspect of the landscape that shows how steep the ground surface is is its slope. It offers crucial details regarding the regionally oriented geological and geodynamic processes [38]. The surface's slope has a big impact on surface runoff and infiltration rates [39]. Less recharge occurs at higher slope angles because precipitation quickly cascades down steep hills during a downpour. The Rarhu watershed's slope map is shown in Fig. 9. The slope values were reclassified and divided into five groups: extremely steep (23.80–66.67), steep (14.65–23.79), medium (8.38–14.64), mild (4.19–8.37), and level (0–4.18). Slopes that are level and mild are given a higher weight, whilst steep and extremely steep slopes are given a lower weight.
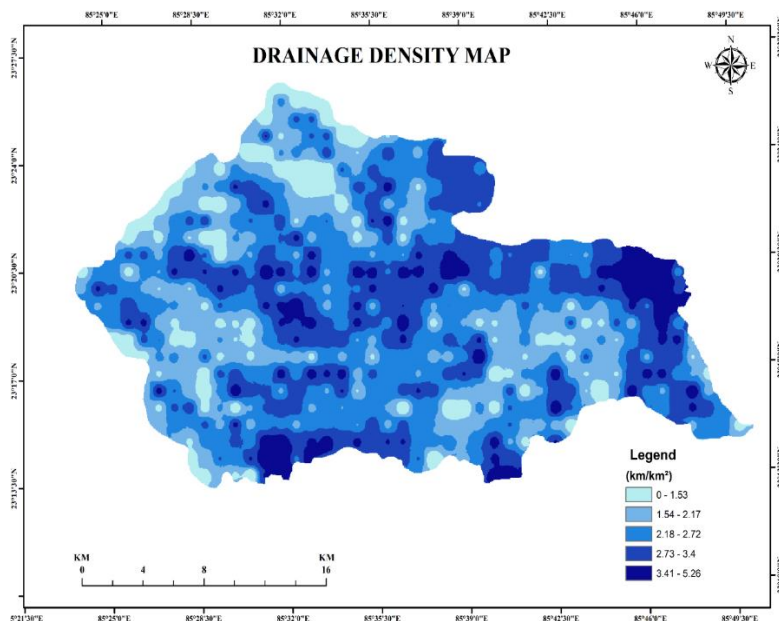


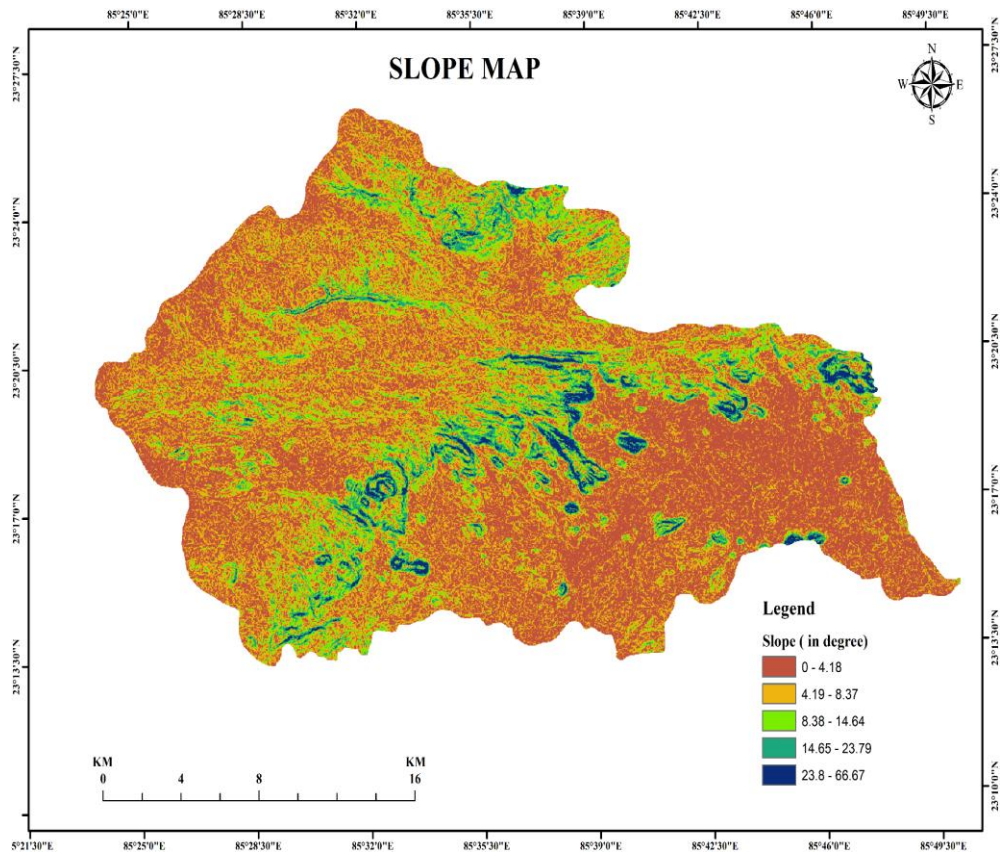**Fig. 8. Showing the Drainage density map of the study area**

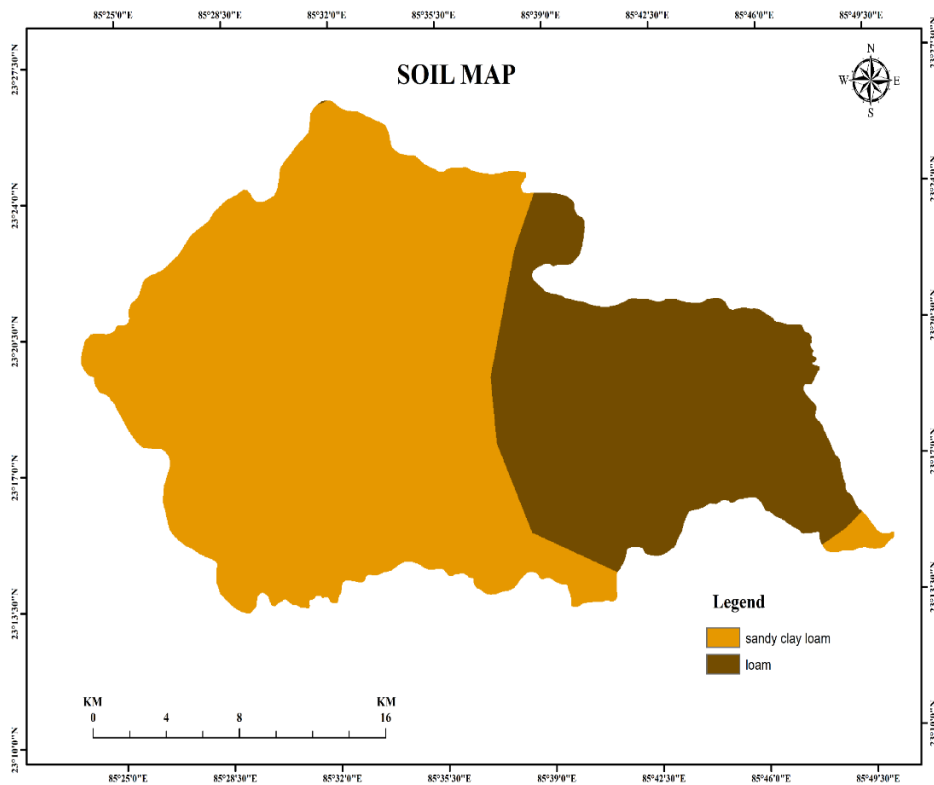**Fig. 9. Showing the slope map of the study area**



**Fig. 10. Showing the soil map of the study area.**

### 3.7 Soil

Soil classes are pivotal in determining the volume of water that can infiltrate into subsurface formations, thereby influencing groundwater recharge [37,40]. When evaluating infiltration rates, soil texture and hydraulic properties are important considerations. The soil map of the Rarhu watershed, shown in Fig. 10, shows the several soil groups sandy clay loam and, loam that were determined using the (FAO) soils. Sandy clay loam soils demonstrate superior infiltration rates in contrast to loam soils, a trait pivotal in influencing infiltration dynamics. This elevated infiltration capacity observed in sandy soils, relative to loam soils, can be attributed to their distinctive textural and structural attributes. Consequently, within the framework of groundwater potential mapping, greater emphasis was placed on the sandy clay loam soil classification to accommodate its heightened efficacy in facilitating infiltration and consequent groundwater replenishment [41].

### 3.8 Rainfall

Rainfall is the main supply of water for the hydrological cycle and has the greatest impact on the dynamics of groundwater in a given area. The study included rainfall data spanning from 1992 to 2022, with an annual rainfall range of 1040mm to 1369mm. Using spatial analysis tools and the Raster calculator, a rainfall spatial distribution map was produced. Based on average values, rainfall was categorized into five groups: Very Low (1040.46–1089.48 mm), Low (1089.49–1151.4 mm), Moderate (1151.41–1215.9 mm), High (1215.91–1293.3 mm), and Very High (1293.31–1363.41 mm). Infiltration is contingent upon rainfall intensity and duration. High-intensity, short-duration rainfall tends to result in less infiltration and more surface runoff, whereas low-intensity, long-duration rainfall encourages higher infiltration than runoff [37]. Areas with heavy rainfall receive higher weights, and vice versa. The rainfall spatial interpolation map for the Rarhu watershed is shown in Fig. 11.

### 3.9 Topographic Wetness Index (TWI)

The Topographic Wetness Index (TWI), which measures the possible groundwater infiltration driven by topographical factors, is widely used to evaluate the influence of topography on hydrological processes [42]. TWI calculation employed the "Hydrology tool," a model simulating hydrologic water fluxes throughout the watershed. TWI values in the study area ranged from 1.67 to 20.32. These values were categorized into five groups: 1.67–5.04, 5.05–6.72, 6.73–9.06, 9.07–12.35, and 12.36–20.32. Higher weights were assigned to areas with higher TWI values, and lower weights to those with lower TWI values. Fig. 12 shows the Topographic Wetness Index (TWI) map for the Rarhu watershed. The following equation (3) was used to calculate the TWI values:

$$TWI = \ln \frac{\alpha}{\tan \beta} \tag{3}$$

β=Slope-related topographic gradient; α=upslope contributing area.

### 3.10 Curvature

Concave upward or convex upward profiles are examples of surface profiles whose curvature can be used to quantitatively indicate their nature [32]. In convex and concave profiles, water tends to accumulate and decelerate, respectively. Within the research area, the curvature ranges varied from 21.76 to -30.72. Five classes (-30.72 to -2.11, -2.10 to -0.67, -0.66 to 0.56, 0.57 to 2.41, and 2.42 to 21.76) were created from the reclassification of these values (Fig. 13). those with greater curvature values were given more weight, whereas those with lower curvature values were given less weight. The Rarhu watershed's curvature map is shown in Fig. 13.

### 3.11 Groundwater Potential Zone (GWPZ)

Throughout the last five to six decades, several anthropogenic activities and imbalanced development have significantly reduced the recharge of groundwater, a replenishable resource. Comprehending the potential of groundwater is essential for the sustainable development and planning of a region. Because groundwater availability fluctuates across time and space, precise and thorough evaluations of groundwater resources are required. Parameters Including Geomorphology, Geology, Land Use/Land Cover (LULC), Lineament, drainage density, Slope, Soil, Rainfall, Curvature, and, Topographic Wetness Index (TWI) are considered in this study. The weighted overlay method was employed to delineate groundwater potential zones of the Rarhu Watershed. The resulting map categorizes areas into high, moderate, and low groundwater potential zones, covering an aerial spread of 50.60 km², 329.25 km², and 220.68 km² respectively (Table 7). The majority of high groundwater potential zones are

located in midstream and downstream regions, typically in areas characterized by substantial rainfall and high infiltration potential. Valleys and places with high drainage densities are typical locations for zones with moderate groundwater potential. Low groundwater potential zones are less common in midland regions and more common in highlands and lowlands (Fig. 14). The Gneiss complex, steep slopes, high drainage density, and conserved forests are all linked to these low potential zones. To further validate the delineated groundwater potential zones, the results obtained in this study were compared against observation well data from the Central Ground Water Board (CGWB). For this purpose, a comprehensive analysis was conducted on a total of 32 observation wells located within the study area. The groundwater levels and yields recorded at these observation wells were cross-referenced with the mapped groundwater potential zones, providing an additional layer of verification for the study's findings.

## 3.12 Validation of GPZ

The range of values for the area under the curve (AUC) is 0.5 to 1.0. According to Rasyid et al., [43], the AUC can be divided into five classes for improved predictive performance evaluation: 0.5–0.6 (unacceptable discrimination), 0.6–0.7 (bad discrimination), 0.7–0.8 (acceptable discrimination), 0.8–0.9 (good discrimination), and 0.9–1.0 (outstanding discrimination). The greater discriminating and prediction power of the model is shown by higher AUC values. To validate the delineated groundwater potential zones, a comprehensive dataset was compiled, consisting of 32 observation wells (including borewells, tube wells, and dug wells) and 16 non-well point locations. The spatial coordinates were gathered during field surveys in May 2023 using Garmin Etrix 30x GPS receivers. Borewell and dug well locations from the Central Ground Water Board (CGWB, 2022), Ranchi Jharkhand supplemented the field data. This dataset served as a reference for evaluating the accuracy and reliability of the groundwater potential zone mapping. The AUC analysis yielded a value of 0.877, indicating a considerably acceptable accuracy for the predicted groundwater potential zones (GPZs) model (Fig. 8). ROC curve analysis confirmed the effective prediction of GPZs using the Analytical Hierarchy Process (AHP) methodology, with an AUC value of 0.877. According to Rasyid et al.,[43], an AUC value within the 0.8–0.9 range signifies very good acceptable model discrimination and predictive performance (Fig. 15). Thus, the obtained AUC value validates the robustness of the AHP-based approach for delineating groundwater potential zones in the study area.
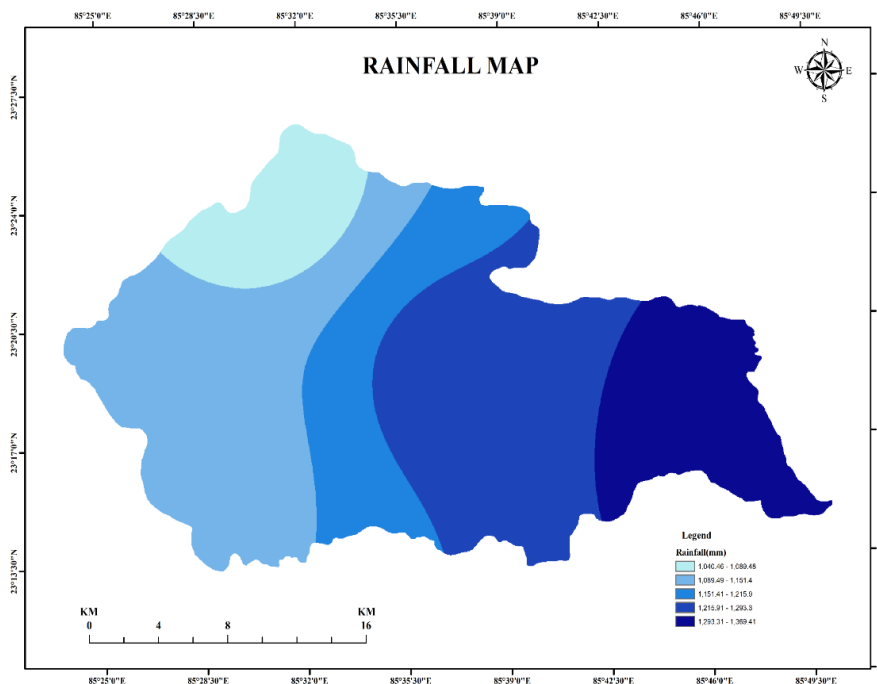


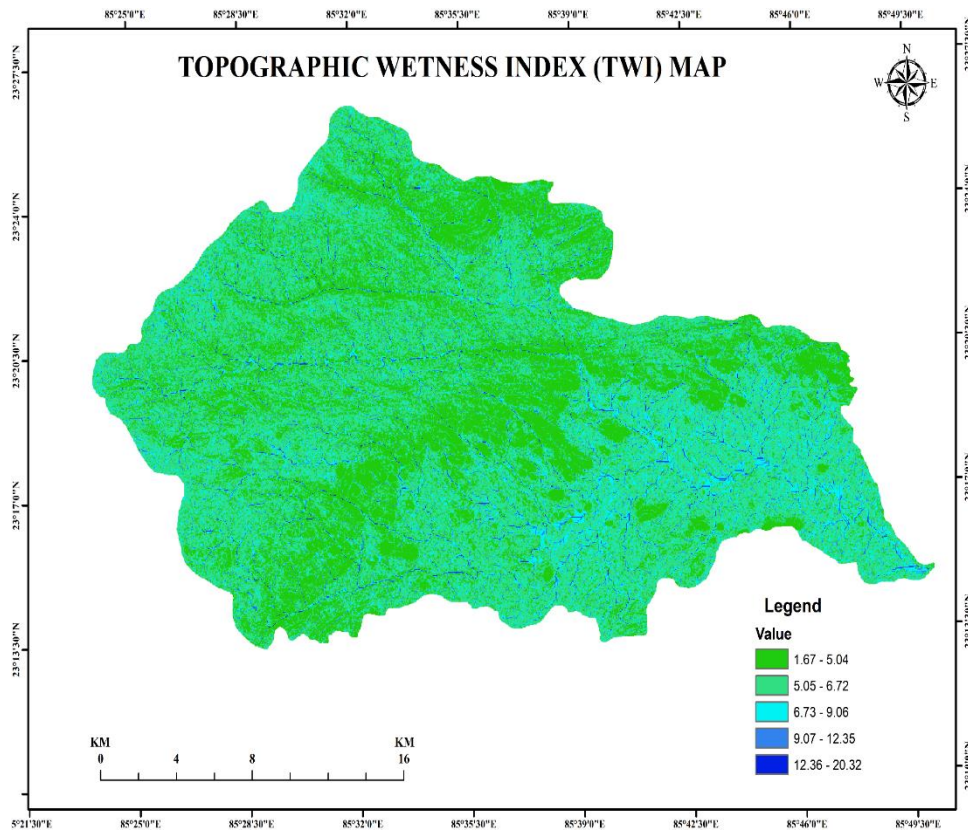**Fig. 11. Showing the rainfall map of the study area**

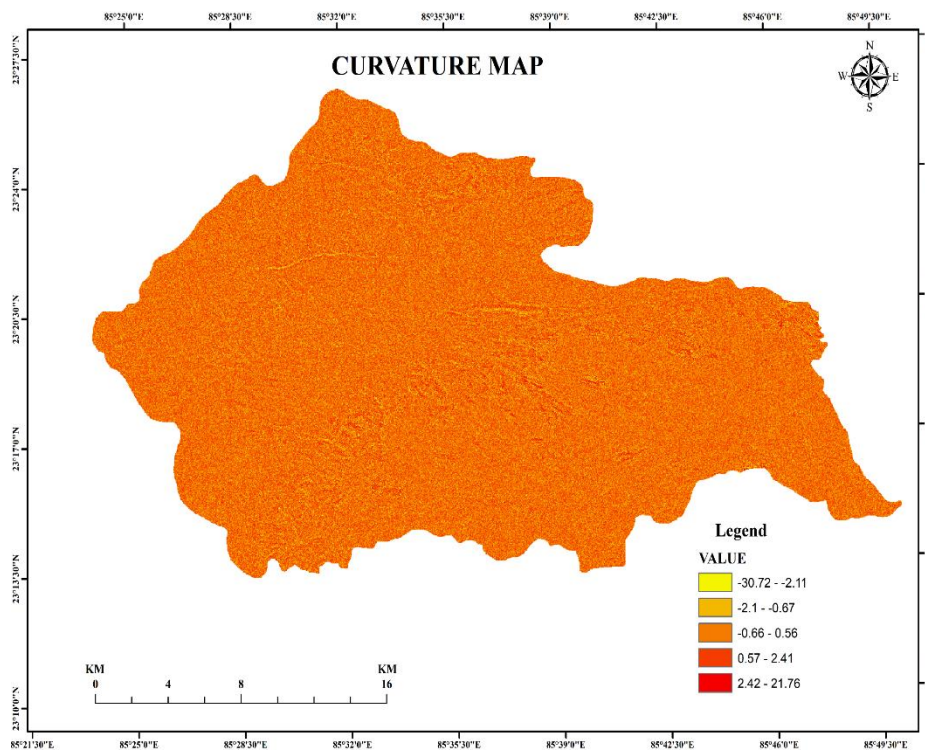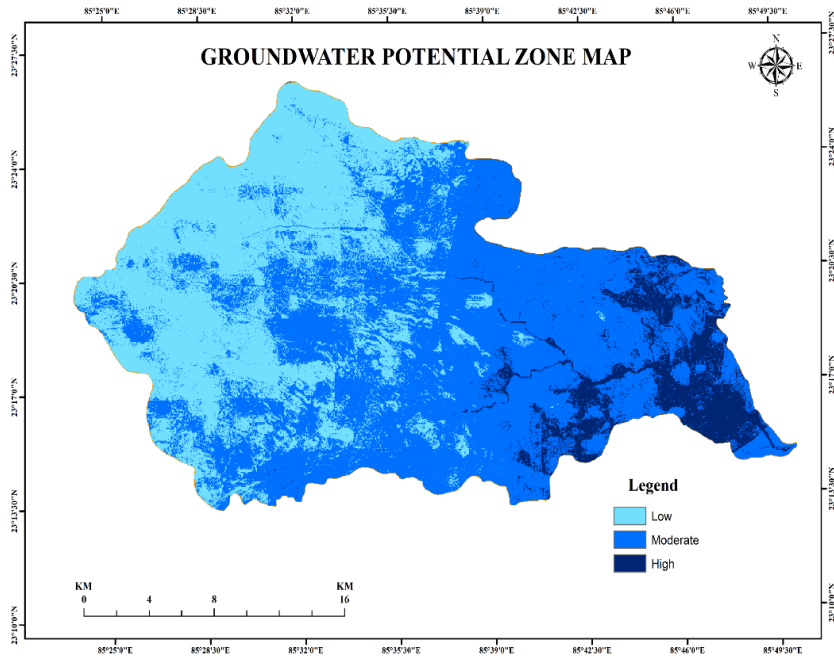**Fig. 12. Showing the TWI map of the study area**



**Fig. 13. Showing the curvature map of the study area**

**Table 7. The extent of groundwater potential zones identified in the study area**

| GWPZ Class | Area (Km2) | Area % | Potential Capacity |
|---|---|---|---|
| Low | 220.68 | 36.75 | Poor |
| Moderate | 329.25 | 54.83 | Moderate |
| High | 50.60 | 8.43 | Good |
| Total | 600.53 | 100 | |



**Fig. 14. Showing the groundwater potential zone (GWPZ) map of the study area**
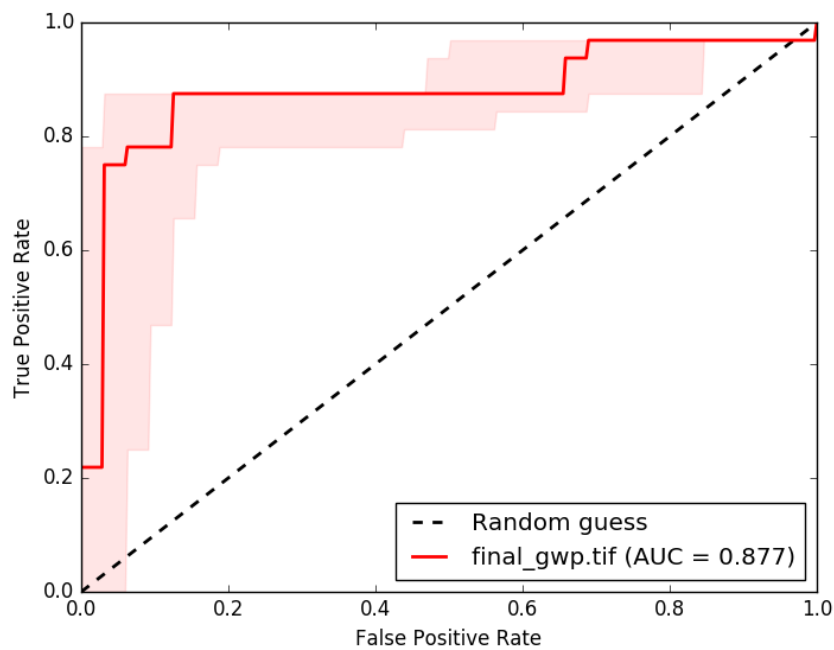


**Fig. 15. Showing Visual representation of the model validation results utilizing the Receiver Operating Characteristic (ROC) curve and the associated Area Under the Curve (AUC) metric**

## 4. CONCLUSIONS

The current study aims to map groundwater potential zones in the Rarhu River watershed, a small dry tropical region in east India, by employing a blend of AHP and GIS techniques. This watershed lies on the eastern side of the Ranchi plateau and the western side of the Purulia hills. The final groundwater potential zone map facilitated the categorization of the study area into three distinct classes: high, moderate, and, low potential zones. The spatial distribution of these zones revealed that the high-potential zones are predominantly situated in the lower catchment and middle reaches of the river. In contrast, the low and moderate potential zones are primarily located within the medium to high altitudes and, migmatite complex formation region of the watershed. The moderate potential zone exhibits a widespread distribution, encompassing 53.83% of the total study area. The high and low potential zones cover 8.43 % and 36.75 % of the area, respectively. This spatial distribution pattern of groundwater potential zones is influenced by the interplay of various hydrogeological factors, including geological formations, geomorphological features, and hydrological characteristics of the watershed. The groundwater potential zone map provides insights for decision-makers on groundwater planning and management for urban and agricultural purposes. As most of the study area is agricultural land, the findings can help improve irrigation facilities and enhance agricultural productivity. By identifying areas with varying groundwater prospectivity, the map supports sustainable groundwater utilization strategies tailored to the region's hydrogeological conditions and water demands. It serves as a valuable decision-support tool for stakeholders to develop informed strategies for judicious groundwater management.

## 5. LIMITATIONS OF THE STUDY

The geological complexity of the study areas poses a significant challenge for this research. Determining groundwater potential zones is complicated by the heterogeneity resulting from various rock types, geological formations, and structural features like folds and faults. Additionally, uncertainties related to hydrogeological factors, particularly hydraulic conductivity, can greatly affect the precision of zone definitions. The lack of thorough understanding of these hydrogeological characteristics inherently obscures the results of groundwater potential mapping efforts. Integrating advanced modeling tools and high-resolution data is essential for future research endeavors to enhance the reliability of groundwater potential assessments in light of these geological and hydrogeological complexities.

## DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI Technologies such as Large Language,Models (CHAT GPT,COPILOTetc) and text –to-image generators have been used during writing or editing the manuscript.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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