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Integrated AHP and GIS-Based Delineation of Groundwater Potential Zones in the Tipan River Basin, India: A Multi-Criteria Decision and Sensitivity Analysis Approach

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Abstract

The Tipan River, a tributary of Son River in Madhya Pradesh, India, is characterized by diverse geomorphic features such as pediment-pediplain complexes, low to moderately dissected hills, and an intricate river network. The soil of region ranges from clayey to loamy, underlain by geological formations including basalt, granite gneiss, limestone, and fine-grained sandstone. To address urgent need for sustainable groundwater management, this study integrates the Analytical Hierarchy Process (AHP) with Geographic Information System (GIS) tools to delineate groundwater potential zones (GWPZs). Eight hydrological parameters - rainfall, geology, geomorphology, soil, land use/land cover (LULC), slope, drainage density, and lineament density—were selected based on their relevance to groundwater occurrence and recharge. These were weighted through AHP using Saaty's 1–9 scale, with consistency verified (CI = 0.055, CR = 0.039). A weighted overlay analysis in ArcGIS Pro produced a GWPZ map, classifying basin into four classes: Poor (3.58%), Moderate (20.62%), Good (47.59%), and Very Good (28.21%). High groundwater potential was found in areas with gentle slopes, loamy soils, pediment-pediplain features, and high rainfall. The map's accuracy was validated using Receiver Operating Characteristic (ROC). Area Under Curve (AUC) value of 0.789, indicates strong predictive performance. Sensitivity analysis through the map removal method highlighted geology, geomorphology, and soil as the most influential parameters, while LULC showed minimal impact. This AHP-GIS approach offers a robust and replicable framework for groundwater assessment, supporting sustainable water resource planning in Tipan River Basin.

Keywords: Tipan River Basin, Analytical Hierarchy Process, Geographic Information System, Groundwater Potential Zones, Sensitivity Analysis

Introduction

Groundwater, a critical natural resource, serves as a basic source of potable water, irrigation, as well as industrial use in many regions worldwide, particularly in semi-arid and arid environments (Magesh *et al.*, 2012; Pal *et al*., 2020; Sherin *et al*., 2023; El-Sorogy *et al*., 2024). In India, groundwater accounts for approximately 50% of irrigation needs and over 80% of rural and urban water supplies, underscoring its significance for sustainable development and food security (Das, 2019). However, the increasing demand for groundwater, coupled with overexploitation, climate variability, and inadequate management, has led to significant depletion of aquifers, posing challenges to water security (Machiwal *et al*., 2011; Kumar *et al*., 2021; Shinde *et al*., 2024). The Tipan River Basin, located in central India, exemplifies these challenges, with its diverse geological settings and growing anthropogenic pressures necessitating precise and reliable methods for assessing groundwater potential.

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Delineating zones of groundwater potential (GWPZs) is essential for planning and management of groundwater resources as it enables informed management and planning of water resource (Oh *et al.*, 2011; Manap *et al.*, 2013; Nagarajan and Singh, 2009; Hasanuzzaman *et al.*, 2022; Masroor *et al.*, 2023). Traditional methods like geophysical surveys are often expensive, time-consuming, and offer limited spatial coverage. (Tiwari and Kushwaha, 2020; Shimpi and Rokade, 2021; Takele *et al.*, 2025). In contrast, combination of geospatial techniques, including Geographic Information Systems (GIS) and remote sensing, with multi-criteria decision-making methods such as Analytical Hierarchy Process (AHP), offers a robust, cost-effective, and spatially comprehensive approach to mapping groundwater potential (Echogdali *et al.*, 2022; El Sherbini *et al.*, 2025; Sarkhel, 2025). These methods leverage spatial data, including topography, lithology, land use/land cover (LULC), rainfall, and drainage patterns, to model groundwater potential with high accuracy (Chatterjee *et al.*, 2023; Verma and Mirajkar, 2024).

AHP scale developed by Saaty (1980), is a broadly used MCDA method that assigns weights to influencing factors, with sensitivity analysis enhancing the reliability and robustness of

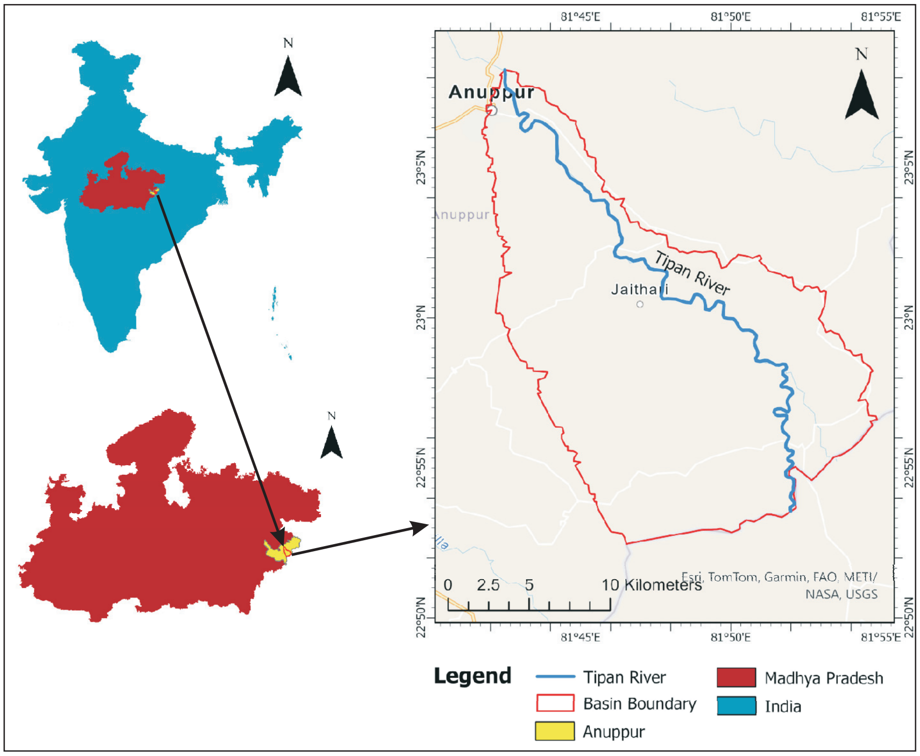

Fig.1. Location map of Tipan River Basin

results (Obeidavi *et al.*, 2021; Tiwari *et al.*, 2022). Its application in groundwater studies has been well-documented, with studies demonstrating its efficacy in diverse geological settings (Nguyen *et al.*, 2020; Thounaojam and Oinam, 2025; Suryawanshi *et al.*, 2025). By integrating AHP with GIS, researchers can generate spatially explicit groundwater potential maps that account for the complex interplay of hydrogeological, geomorphological, and climatic factors (Masoud *et al.*, 2022; Prapanchan *et al.*, 2024). Furthermore, sensitivity analysis enhances the reliability of these models by evaluating the robustness of the results to variations in input parameters, addressing uncertainties inherent in subjective weighting schemes (Ahmed and Mansor, 2018; Obeidavi *et al.*, 2021; Taibou *et al.*, 2025).

Recent groundwater mapping uses machine learning for higher accuracy, while AHP offers a simpler, data-efficient, and interpretable alternative, ideal for areas with scarce hydrogeological information (Moghaddam *et al.,* 2020; Bai *et al.*, 2022; Pappaka *et al.*, 2025). Despite the extensive application of AHP and GIS in groundwater studies, their application continues to evolve, particularly in complex terrains such as transitional zones (Miraki *et al.*, 2019; Pham *et al.*, 2019; Zhao *et al.,* 2024; Alamirew *et al.*, 2025).

This study addresses these opportunities by applying a robust AHP-GIS methodology, enriched with sensitivity analysis and modern remote sensing inputs, to identify groundwater potential zones in Tipan River Basin. Tipan River Basin, characterized by its complex geology, variable rainfall patterns, and increasing agricultural demands, presents an ideal case study for addressing these gaps. Previous studies in central India have highlighted the need for integrated approaches to delineate GWPZs in regions with similar hydrogeological challenges (Manjare and Pophare, 2020; Tiwari *et al.*, 2024). This research is particularly focused on increasing stress on groundwater resources in central India, where rapid urbanization, agricultural intensification, and climate variability exacerbate water scarcity (Tiwari and Kushwaha, 2020; Prapanchan *et al.*, 2024).

The aim of this research is to develop a reliable and spatially explicit groundwater potential map for Tipan River Basin using a multi-criteria decision and sensitivity analysis approach. Specifically, study objectives are: (1) to identify and prioritize key hydrogeological and geomorphological factors influencing groundwater potential using AHP; (2) to integrate high-resolution geospatial datasets, and conventional hydrogeological data, within a GIS framework; (3) to delineate GWPZs and classify them into zones; and (4) to conduct sensitivity analysis to assess the robustness of model outputs and identify the most influential factors.

Study Area

The Tipan River Basin, located between 22°50' to 23°10' North latitude and 81°40' to 81°55' East longitude, spans an area of approximately 339.23 km² and comes under Survey of India toposheets no. 64E/12, 64E/16 and 64F13, on a scale of 1:50,000 (Fig.1). The basin's elevation varies from 490 to 976 meters above sea level, as derived from Digital Elevation Model (DEM). Region is characterized by diverse geomorphic features including Low and Moderately Dissected Hills and Valleys, Pediment-Pediplain Complex, and a network of river and waterbody systems. The dominant soil types in the basin are clayey and loamy soils, as identified by the Central Ground Water Board (CGWB). Geologically, the basin comprises Basalt, Granite Gneiss, Limestone, and Fine-Grained Sandstone formations. The slope gradient ranges between 0.001° to 26.632°, contributing to surface runoff and erosion potential. Annual rainfall varies from 1,137.246 mm to 1,248.769 mm.

Methodology

In this study, eight key parameters: lineament density, rainfall, geology, geomorphology, soil, land use/land cover (LULC), slope, and drainage density, were selected based on their proven relevance in groundwater potential zone (GWPZ) mapping (Fig. 2). These factors collectively influence groundwater recharge, storage, and movement. Weights were assigned through AHP, and map removal sensitivity analysis was conducted to evaluate relative influence of each thematic layer on GWPZ outcomes, thereby ensuring robustness and reliability of the model (Shinde *et al.*, 2024; Verma and Mirajkar, 2024). The pairwise comparison matrix and Saaty's 1–9 scale were used to evaluate the comparative significance of each parameter, where 1 denotes equal influence and 9 represents extreme dominance of one factor over another (Table 1).

While AHP–GIS integration is a well-established approach in groundwater studies, the novelty of this research lies in its comprehensive integration of high-resolution remote sensing–derived LULC data with sensitivity analysis, which allows for a finer assessment of spatial variability in recharge potential. Furthermore, the combined interpretation of Sensitivity Index (SI), Effective Weight (W), Mean (M), and Standard Deviation (SD) provides deeper insight into how parameters such as rainfall, geology, and geomorphology exert dominant control over groundwater potential in Tipan River Basin. This dual focus on high-resolution spatial analysis and quantitative sensitivity evaluation enhances the precision of GWPZ delineation and offers a more reliable framework for basin-scale groundwater management under changing land use and climatic conditions.

Validation Groundwater Potential Zone Mapping

To ensure the reliability of the GWPZ map, a validation process was carried out by overlaying the locations of 60 existing wells onto the final GWPZ map. The accuracy of map is assessed using ROC curve, generated through AUC tool in ArcGIS Pro, providing a quantitative measure of model performance.

Sensitivity Analysis

A sensitivity analysis was conducted using map removal method (Obeidavi *et al.*, 2021) to evaluate impact of each thematic layer on overall GWPZ outcome and to test the robustness of the weight assignments made through AHP. This technique involves sequentially eliminating one layer at a time and assessing its influence on Groundwater Potential Index (GWPI).

Table 1: Pairwise comparison matrix of different factors influencing GWPZ

Matrix	Dd	Gm	S	LULC	Ld	Sp	R	G
Drainage Density	1	2	3	4	4	5	6	7
Geomorphology	1/2	1	2	3	3	4	5	6
Soil	1/3	1/2	1	2	2	3	4	5
LULC	1/4	1/3	1/2	1	2	3	4	5
Lineament Density	1/4	1/3	1/2	1/2	1	2	3	4
Slope	1/5	1/4	1/3	1/3	1/2	1	1/2	3
Rainfall	1/6	1/5	1/4	1/4	1/3	2	1	2
Geology	1/7	1/6	1/5	1/5	1/4	1/3	1/2	1

**Rainfall (R); Geology (G); lineament density (Ld), slope (Sp); drainage density (Dd); soil(S)

Table 2: Determination of standardized weights for each factor influencing GWPZ

Matrix	R	G	Gm	S	LULC	Sp	Dd	Ld
Drainage Density	0.35	0.42	0.39	0.35	0.31	0.25	0.25	0.21
Geomorphology	0.18	0.21	0.26	0.27	0.23	0.20	0.21	0.18
Soil	0.12	0.10	0.13	0.18	0.15	0.15	0.17	0.15
LULC	0.09	0.07	0.06	0.09	0.15	0.15	0.17	0.15
Lineament Density	0.09	0.07	0.06	0.04	0.08	0.10	0.13	0.12
Slope	0.07	0.05	0.04	0.03	0.04	0.05	0.02	0.09
Rainfall	0.06	0.04	0.03	0.02	0.03	0.10	0.04	0.06
Geology	0.05	0.03	0.03	0.02	0.02	0.02	0.02	0.03

$\lambda_{max} = 8$ Consistency Index (CI) = 0.055
Random Index (RI) = 1.41 Consistency Ratio (CR) = 0.039

**Rainfall (R); Geology (G); lineament density (Ld), slope (Sp); drainage density (Dd); soil(S); normalized weights (NW).

The Sensitivity Index (S) was calculated using the following formula:

$$S = [((GWPI/N) - (GWPI'/n)) / GWPI] \times 100$$

Where: S = Sensitivity Index, $GWPI$ = Index using all layers, $GWPI'$ = Index after removing one layer, N and n = Number of layers in full and reduced models respectively

To quantify each layer's contribution, the Effective Weight (W) was determined using:

$$W = (P_r \times P_w / G_P) \times 100$$

Where: W = Effective weight (%), P_r = Rank value of the layer, P_w = Assigned weight, G_P = GWPI with all layers

G_P = GWPI with all layers

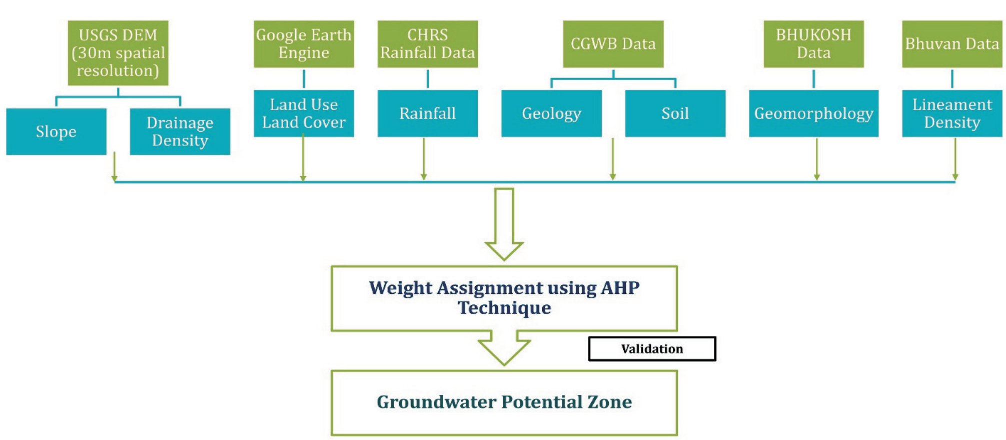

Fig.2. Methodology flowchart

AHP Consistency Check

This was employed to assign weights based on expert judgment and literature. To ensure logical consistency in pairwise comparisons, the Consistency Ratio (CR) was calculated:

$$CR = CI / RI$$

Where: *CI* = Consistency Index, *RI* = Random Index based on number of criteria

The CI is derived using:

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

Where λ_{max} = Principal eigenvalue, *n* = Number of criteria

Normalized weights were derived using the eigenvector method, which reduces subjectivity. The consistency of judgments in the pairwise matrix was evaluated through CI and CR. With CI ≈ 0.055 and CR ≈ 0.039 (CR < 0.1), comparison matrix showed a high level of consistency (Table 2). The final weights were used in a weighted overlay analysis performed in ArcGIS Pro. All thematic layers were changed to raster format, and each class was ranked and weighted (Table 3). This integration produced the GWPZ map, identifying zones with varying groundwater potential across the Tipan River Basin.

Table 3: Ranking of factors influencing GWPZ

Thematic Layers	Weigh-tage	Classes	Rank (Saaty, 1980)
Drainage density (in km/km^2)	31.92	0.001 - 49.141	9
		49.142 - 98.282	7
		98.283 - 147.423	5
		147.424 - 196.564	3
		196.565 - 245.704	1
Geomor-phology	21.90	Low Dissected Hills and Valleys	5
		Moderately Dissected Hills and Valleys	3
		Moderately Dissected Plateau	1
		Pediment Pediplain Complex	7
		Waterbodies-Other	8
		Waterbody - River	9
Soil	14.45	Clayey Soil	3
		Loamy Soil	9
LULC	11.47	Water bodies	9
		Forest	7
		Vegetation	5
		Agriculture	4
		Built up	1
		Barren land	3
Lineament density (in km/km^2)	8.37	0.001 - 0.169	1
		0.17 - 0.338	3
		0.339 - 0.507	5
		0.508 - 0.676	7
		0.677 - 0.845	9
Slope (in degree)	4.71	0.001 - 5.326	9
		5.327 - 10.653	7
		10.654 - 15.979	5
		15.98 - 21.306	3
		21.307 - 26.632	1
Rainfall (in mm)	4.55	1,137.246 - 1,174.027	1
		1,174.028 - 1,189.678	3
		1,189.679 - 1,196.337	5
		1,196.338 - 1,211.988	7
		1,211.989 - 1,248.769	9
Geology	2.62	Basalt	5
		Fine Grained Sandstone	7
		Granite Gneiss	3
		Limestone	9

Results and Discussion

Drainage Density

Tipan River, a sub-basin of Son River located in Anuppur district, flows in a south–northwest direction before joining the Son. Drainage density plays a critical role in surface hydrology by influencing how quickly runoff is conveyed across a landscape (Pal *et al.*, 2020). Due to slow infiltration and recharge, areas with high drainage density quickly drain surface water, reducing subsurface recharge. Thus, densely drained regions usually exhibit lower groundwater potential (Das, 2019). In Tipan River basin, drainage density was classified into five zones based on calculated values ranging from 0.001 to 245.704. Zone 1, with the lowest drainage density (0.001–49.141), covers the largest area about 147.47 km² (43.52%) of basin, indicating good potential for groundwater recharge. Zone 2 (49.142–98.282) accounts for 26.32% of area, followed by Zone 3 (98.283–147.423) at 19.87%, both representing moderate recharge potential (Fig. 3). Meanwhile, Zones 4 and 5, which exhibit the highest drainage densities (147.424–245.704), together comprise only 10.28% of the basin area (9.08% and 1.20%, respectively), and are considered to have poor potential due to rapid surface runoff and minimal infiltration (Fig. 3). The dominance of low to moderate drainage density zones is consistent with findings from nearby basins of Central India, such as Son River sub-basin (Rai *et al.*, 2017) and Sidhi area (Tiwari and Kushwaha, 2020), where similar geomorphic and lithologic conditions promoted low drainage densities and consequently higher groundwater potential.

Geomorphology

The geomorphology of basin reflects a diverse landscape shaped by a combination of denudational, structural, and fluvial processes (Davoodi Moghaddam *et al*., 2015). The basin features low to moderately dissected hills, valleys, plateaus, pediment–pediplain complexes, and river systems (Fig. 4). Dominated by pediment–pediplain complex covering 279.05 km² (82.26%), this geomorphic unit, with its gentle slopes and deeper weathered zones, is generally favorable for groundwater recharge and supports better subsurface water storage. Moderately dissected plateau, comprising 10.37% of the basin (35.19 km²), also contributes to moderate groundwater potential, though less significantly than the pediplain areas. In contrast, low and moderately dissected hills and valleys, occupying 1.79% (6.08 km²) and 4.08% (13.84 km²) respectively, are typically rugged and resistant terrains that promote surface runoff, offering limited groundwater potential. Waterbodies, including rivers (1.11%) and other water features (0.39%), collectively make up about 1.5% of the area. The predominance of pediment–pediplain units in Tipan basin aligns with geomorphic characteristics reported in Central Indian basins such as Hanumana Block (Tiwari *et al.*, 2022) and Sidhi area (Tiwari and Kushwaha, 2020), where pediplain-dominated terrains were found to be the most conducive to groundwater accumulation. This similarity underscores a recurring geomorphic control over recharge across Son sub-basins.

Soil

Soil plays a vital role in controlling porosity, permeability,

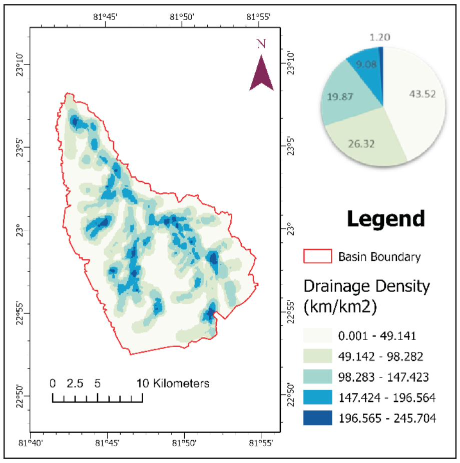

Fig.3. Drainage density of Tipan River Basin

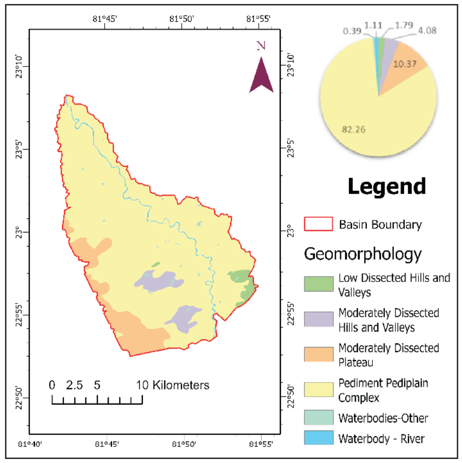

Fig.4. Geomorphology map of Tipan River Basin

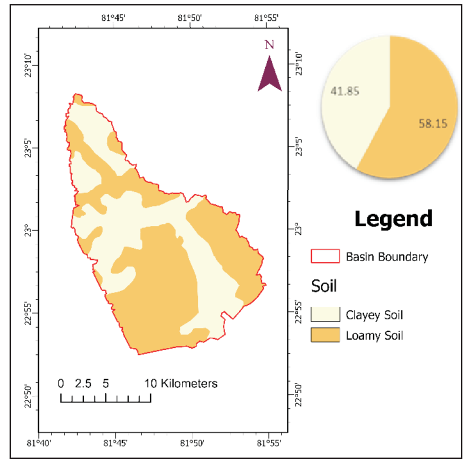

Fig.5. Soil map of Tipan River Basin

and overall hydrological behavior of a region, making it a key factor in the delineation of GWPZs (Hussein *et al.*, 2017). Coarse-textured soils like loamy soil, rich in sand, have higher permeability and porosity, allowing better water movement and promoting groundwater recharge (Fatema *et al.*, 2023). In contrast, fine-textured clayey soils have low permeability, restricting infiltration and increasing surface runoff due to their compact structure and smaller pore spaces. In study basin, loamy soil dominates the basin, covering 197.15 km² (58.15%), offering high groundwater recharge potential due to good infiltration. The remaining 41.85% of area (141.86 km²), is covered by clayey soil, which tends to retain water on the surface and has lower recharge potential due to its compact nature (Fig. 5). The prevalence of loamy soils aligns with comparable textural properties in Sidhi and Rewa districts (Tiwari *et al.*, 2022), where loamy and sandy loam varieties are associated with increased recharge rates and aquifer yield. Consequently, soil features of study area reinforce its designation as having moderate-to-good groundwater potential.

Land Use Land Cover

It is an important factor influencing groundwater recharge. Different land cover types affect volume of water capable of infiltrating into subsurface, making LULC an essential criterion in delineating GWPZs (Truong *et al.*, 2019). The spatial distribution of LULC also provides valuable insights into moisture content, surface runoff behavior, and groundwater availability (Shinde *et al.*, 2024). For the basin, LULC classification was performed using Google Earth Engine and categorized into six distinct classes (Fig. 6). The classification achieved an overall accuracy of 0.84 and a Kappa value of 0.79, both automatically calculated by GEE. Vegetation is the dominant land cover in the basin, occupying 173.05 km² (51.04%) and ranked 5 for its moderate recharge potential, allowing reasonable infiltration while experiencing moderate evapotrans-piration. Barren land and agricultural land follow, covering 17.36% and 17.08% of the area, respectively. Barren land (rank 3) has limited recharge capacity due to its exposed, compacted surfaces, while agricultural land (rank 4) offers moderate infiltration based on soil type and farming practices. Water bodies, covering 7.15%, hold the highest rank (9) for their direct contribution to both surface and subsurface water recharge. Forests, occupying 6.96%, are ranked 7 for enhancing infiltration and reducing runoff. Built-up areas (0.41%) rank lowest (1) due to impervious surfaces that hinder infiltration. The occurrence of vegetative cover and agricultural areas aligns with trends in other Central Indian watersheds, like those examined in Rewa District (Tiwari *et al.*, 2024) and Morna Basin (Manjare and Pophare, 2020).

Lineament Density

Lineaments, which represent linear features such as fractures, faults, and joints in subsurface, are important indicators of groundwater occurrence and movement (Chatterjee *et al.*, 2023). It serves as a key factor in identifying potential groundwater zones. In study area, a lineament density map was prepared using high-resolution satellite imagery. The density values were classified into five categories ranging from 0.001 to 0.845 km/km² (Fig. 7). Each class was ranked according to its suitability for groundwater accumulation, based on Saaty's (1980) scale. The majority of the basin (78.30%), covering 265.43 km², falls within the lowest lineament density range (0.001–0.169 km/km²) and is assigned the lowest rank of 1, indicating very limited potential for groundwater accumulation. This suggests minimal fracturing and structural control over groundwater movement in these areas. Moderate density classes, such as Class 2 (8.09%) and Class 3 (5.85%), with ranks 3 and 5 respectively, suggest moderate potential due to a higher degree of fracturing. In contrast, the areas with the highest lineament densities, Class 4 (5.04%) and Class 5 (2.72%), are considered most favorable zones for groundwater recharge and storage, receiving high ranks of 7 and 9. The spatial trend of low-to-moderate lineament density in the Tipan basin is comparable to that in the Hanumana Block of Rewa District (Tiwari *et al.*, 2022), where similar geological settings produced moderate fracturing and moderate groundwater potential.

Slope

Slope is a vital parameter in assessing groundwater potential, as it directly influences surface runoff, infiltration capacity, and residence time of water on land surface (Bai *et al.*, 2023). Gentle slopes enhance infiltration and groundwater recharge, while steep slopes increase runoff, reducing the potential for water to percolate. Slope analysis was conducted using a DEM, and terrain was classified into five slope categories ranging from 0.001° to 26.632°

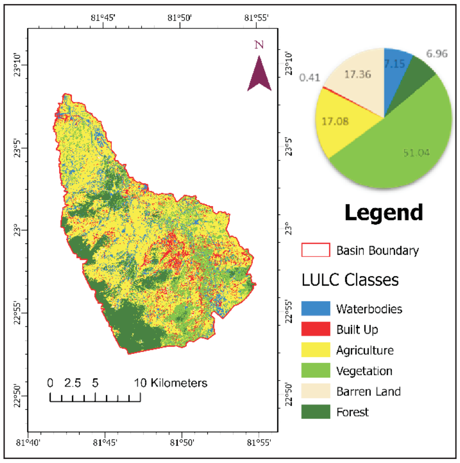

Fig.6. LULC map of Tipan River Basin

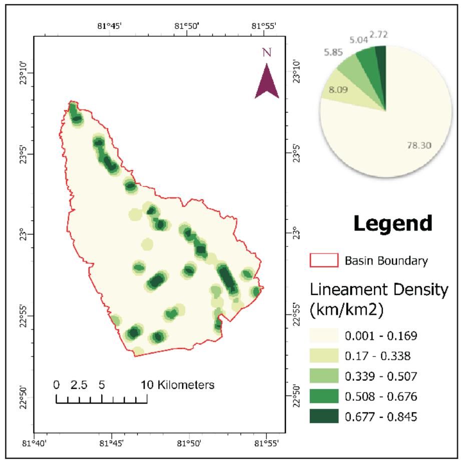

Fig.7. Lineament density map of Tipan River Basin

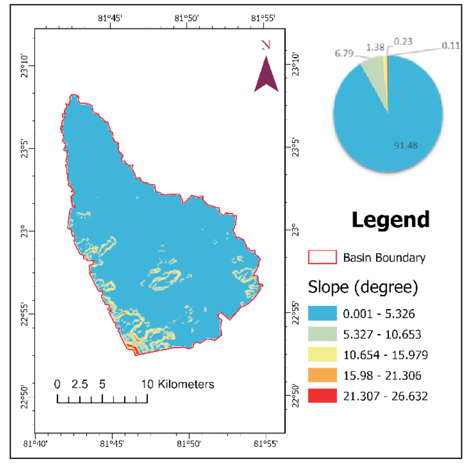

Fig.8. Slope map of Tipan River Basin

(Fig. 8). The analysis revealed that gently sloping areas (0.001–5.326°) dominate the basin, covering 302.42 km² (91.48%) of the total area. These regions, characterized by flat to nearly flat terrain, were assigned the highest rank (9) due to their excellent groundwater recharge potential. Moderate slope zones (5.327–10.653°) account for 6.79% of the area and were given a rank of 7, indicating good recharge capacity, though slightly less favorable than flatter regions. Steeper slope classes are much less prevalent. The slope range 10.654–15.979° covers 1.38% of the basin and was assigned a moderate rank of 5. The steeper slopes 15.98–21.306° and 21.307–26.632° represent only 0.23% and 0.11% of the area, respectively, and received lower ranks of 3 and 1, indicating poor groundwater potential due to rapid surface runoff. This prevalence of gentle slopes aligns with topographic features in Sidhi and Hanumana areas (Tiwari and Kushwaha, 2020; Tiwari *et al.*, 2022), where more than 80% of the basin displayed comparable slope profiles, promoting elevated infiltration rates and designating most areas as having "Good" groundwater potential.

Rainfall

As a tropical country, India relies heavily on rainfall for its water supply. In areas lacking surface water sources, rainfall serves as the primary source for groundwater recharge and hydrological balance (Kumar *et al*., 2021). It is a critical parameter in delineating GWPZs, especially in semi-arid or water-scarce areas. Rainfall distribution data was analyzed and classified into five distinct zones based on the annual precipitation values (Fig. 9). The rainfall in the region ranges from 1,137.246 mm to 1,248.769 mm, and zones. The highest rainfall receiving zone covers 26.22% of the basin and was assigned the highest rank (9) due to its strong contribution to groundwater recharge. Similarly, areas receiving class 2 of rainfall (covering 23.09%) were given a rank of 7, indicating high recharge potential. Moderate rainfall zones account for 10.92% and 29.96% of the area, respectively with corresponding ranks of 5 and 3, reflecting moderate recharge capacity. The lowest rainfall category, 1,137.246–1,174.027 mm, spans 9.81% of the region and was ranked 1, indicating poor groundwater potential due to limited rainfall input. Rainfall variation in Tipan basin shows close resemblance to the climatic regime of nearby Son and Morna sub-basins (Manjare and Pophare, 2020), where mean annual rainfall between 1,000–1,250 mm has been identified as adequate to sustain moderate-to-good recharge levels when supported by permeable soils and gentle topography.

Geology

It plays a foundational role in determining groundwater occurrence and movement, as the type and structure of underlying geological formations directly affect porosity, permeability, and aquifer potential (Tiwari and Kushwaha, 2020). The basin is predominantly underlain by four major geological formations: granite gneiss, fine-grained sandstone, basalt, and limestone. Among these, granite gneiss is the most widespread, covering approximately 214.57 km² (63.29%) of the basin. Although relatively hard and compact, weathered and fractured zones within granite gneiss can store and transmit groundwater, giving it a moderate suitability rank of 5 (Fig. 10). The second most widespread geological unit in the basin is fine-grained sandstone, covering 119.41 km² (35.22%) and ranked highest (9) for groundwater recharge due to its high porosity and permeability (Fig. 10). Sandstones typically allow efficient infiltration and can serve as productive aquifers if not overly cemented. Basalt occupies 1.04% of the area and is ranked 3, reflecting its variable recharge potential. Limestone, though limited to 0.45% of the basin, is ranked 7 for its favorable recharge potential. This lithological configuration closely matches that of other Central Indian basins dominated by sandstone and granite-gneiss complexes (Tiwari *et al.*, 2024; Tiwari and Kushwaha, 2020), where similar geological assemblages have been found to yield moderate-to-good groundwater prospects.

Groundwater Potential Zones

The eight significant parameters were considered to delineate GWPZs. These parameters include rainfall, drainage density, geomorphology, soil, land use/land cover (LULC), lineament density, slope and geology (Tolche, 2020). Using AHP, a pairwise comparison matrix was constructed to assign appropriate weights to each thematic layer and their respective classes. CI and CR for high groundwater potential zones were found to be 0.055 and 0.039, respectively, indicating an acceptable level of consistency in judgment.

The final weighted overlay analysis led to classification of study area into four distinct groundwater potential zones: Poor,

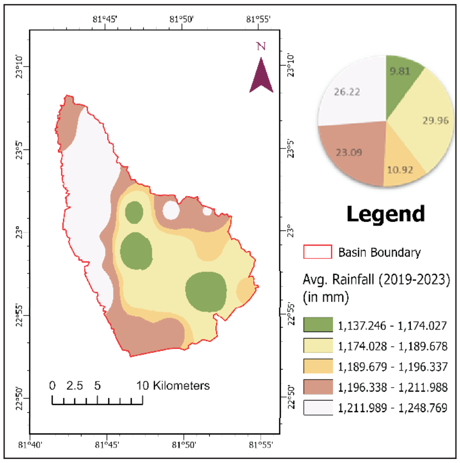

Fig.9. Rainfall map of Tipan River Basin

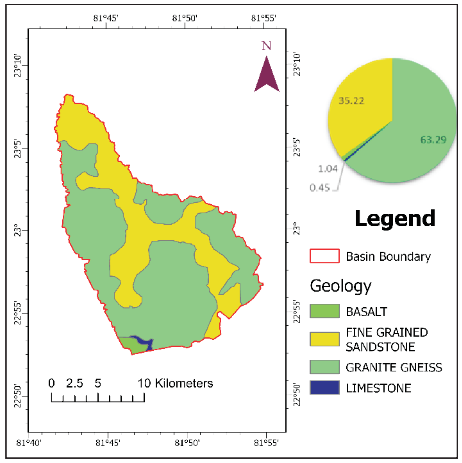

Fig.10. Geology map of Tipan River Basin

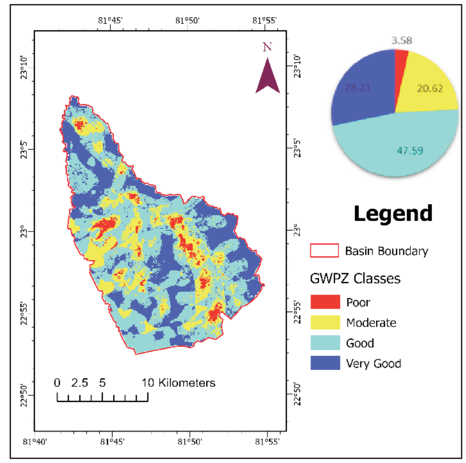

Fig.11. Groundwater Potential Zone map of Tipan River Basin

Moderate, Good, and Very Good, covering 3.58%, 20.62%, 47.59%, and 28.21% of the total area, respectively (Fig. 11). Notably, the majority of basin falls under good category, which indicates favorable conditions for groundwater availability. (Table 4). Therefore, the predominance of "Good" GWPZs in Tipan basin aligns with regional hydrogeological trends across Son sub-basins. This agreement reinforces reliability of AHP-based integrated approach used in delineating groundwater potential zones and highlights the influence of geomorphic and lithologic settings as primary controls on groundwater availability in the region.

Validation

The ROC curve for the Tipan River Basin is presented in figure 12. The AUC highlights the significance of the prediction by illustrating the system's ability to accurately distinguish between "groundwater" and "no groundwater" with balanced precision. The AUC, measured on a 0 to 1 scale, yields a value of 0.789, indicating strong model coherence and higher simulation accuracy. The results showcase excellent performance in generating a groundwater potential map using AHP and RS-GIS technique. The enhanced accuracy of the model (AUC = 0.789) is attributed to its robust handling of uncertain presence of groundwater.

Sensitivity Analysis

A sensitivity analysis was performed to assess relative impact of thematic layers on delineation of GWPZ in the Tipan River Basin, using Sensitivity Index (S), Effective Weight (W), Mean (M), and Standard Deviation (SD) values (Table 5). The results revealed distinct variations in the sensitivity and influence of different parameters.

Geology recorded the highest sensitivity (S: -2.19) despite having the lowest effective weight (W: 8.07%), indicating that even minor changes in geological features can significantly affect GWPZ outcomes. This is because lithological variations control porosity and permeability, which directly determine groundwater storage and flow pathways. Thus, geological heterogeneity plays a decisive role in defining recharge and accumulation zones. These findings underscore the necessity of high-resolution geological mapping and lithological characterization for reliable groundwater assessment and sustainable management.

Slope also exhibited strong sensitivity (S: -1.79, W: 10.90%). Gentle slopes favor infiltration and groundwater recharge, whereas steep slopes promote runoff and reduce recharge potential. This sensitivity highlights the importance of incorporating slope management strategies to enhance infiltration in sloping terrains. Rainfall and drainage density shared equal sensitivity values (S: -1.59), although their effective weights differed (W: 12.28% and 11.09%, respectively). Rainfall emerged as a critical driver of recharge, where higher precipitation enhances infiltration opportunities, while drainage density inversely affects recharge by accelerating surface runoff. The high sensitivity of rainfall indicates that variations in precipitation patterns can substantially alter groundwater potential. Hence, integrating long-term rainfall monitoring and climate modeling into groundwater planning is vital for predicting and managing recharge variability. Among the parameters, geomorphology (S: -0.93, W: 15.21%) and soil (S: -0.96, W: 16.70%) exhibited high effective weights, showing their strong control over groundwater storage and infiltration dynamics. Geomorphological units such as valleys, pediments, and plains serve as key recharge and accumulation zones, while soil texture and structure influence infiltration rates and recharge efficiency. Although their sensitivity is moderate, their consistently high

Table 4: GWPZ Classes data and area distribution

S. No.	GWPZ Classes	Area (in km^2)	Percentage
1.	Poor	11.82	3.58
2.	Moderate	68.02	20.62
3.	Good	157.02	47.59
4.	Very Good	93.08	28.21

Table 5: Sensitivity analysis statistics

	Metrics	Index of Sensitivity Analysis (S)	Effective weight % (W)	Mean (M)	SD
1.	Drainage density	-1.59	11.09	36.57	9.55
2.	Geomorphology	-0.93	15.21	34.87	9.10
3.	Soil	-0.96	16.70	34.94	9.17
4.	LULC	-0.82	17.67	34.58	8.70
5.	Lineament Density	-1.04	16.12	35.15	9.37
6.	Slope	-1.79	10.90	37.09	9.12
7.	Rainfall	-1.59	12.28	36.58	9.55
8.	Geology	-2.19	8.07	38.14	7.16

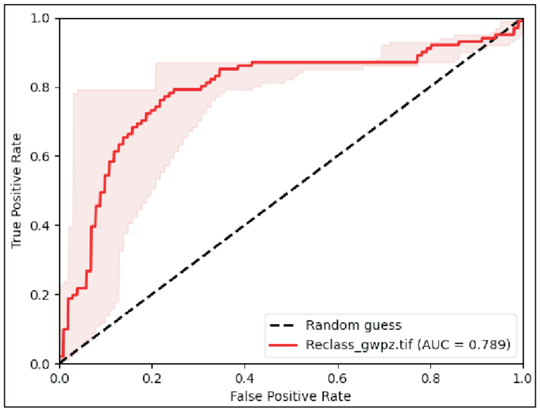

Fig.12. AUC ROC validation of Groundwater Potential Zone

weights demonstrate a steady and reliable influence on groundwater distribution. Prioritizing geomorphological mapping and soil conservation practices can therefore enhance recharge sustainability. Land Use/Land Cover (LULC) had the lowest sensitivity (S: -0.82) but the highest weight (W: 17.67%), indicating that while short-term LULC changes may not drastically alter GWPZ delineation, their cumulative impacts on recharge are substantial. Expanding agriculture tends to enhance infiltration, whereas urbanization reduces recharge potential, emphasizing the importance of land-use regulation and sustainable urban planning in groundwater management. Lineament density (S: -1.04, W: 16.12%) ranked moderate in both sensitivity and weight, reflecting its crucial role in facilitating groundwater movement along fractures and fault zones—particularly in hard rock terrains.

Overall, geology, geomorphology, and soil emerged as the most influential layers due to their direct control on recharge, storage, and subsurface flow, while geology, slope, and rainfall were the most sensitive parameters, showing that variations in these factors have the strongest impact on GWPZ outcomes. The relatively consistent SD values across parameters suggest moderate spatial variability in the basin, supporting a balanced interplay among multiple factors.

Conclusions

This study presents a comprehensive, multi-criteria decision-making approach using the AHP integrated with GIS techniques to delineate GWPZs within the Tipan River Basin. The research utilized eight critical parameters (rainfall, geology, geomorphology, soil, LULC, slope, drainage density, and lineament density) selected based on their hydrological relevance and influence on groundwater occurrence and recharge. Each parameter was weighted through AHP using a pairwise comparison matrix. Consistency in judgment was verified through a Consistency Index (CI = 0.055) and Consistency Ratio (CR = 0.039), confirming reliability of matrix. A weighted overlay analysis was subsequently performed in ArcGIS Pro to integrate these parameters and generate the final GWPZ map. The basin was categorized into four groundwater potential zones: Poor (3.58%), Moderate (20.62%), Good (47.59%), and Very Good (28.21%). The major part of area falls under the 'Good' and 'Very Good' categories, indicating favorable conditions for groundwater availability, particularly in areas characterized by gentle slopes, loamy soils, pediment-pediplain geomorphology, and high rainfall. The reliability of the GWPZ map was further validated using the ROC-AUC method, wherein the spatial correlation between existing well locations. The AUC value of 0.789 indicates a high level of predictive accuracy and validates the effectiveness of the AHP-GIS model in identifying groundwater potential zones. In addition, a sensitivity analysis using the map removal method assessed the influence of each thematic layer on performance of model. Geology, geomorphology, and soil emerged as the most sensitive and influential parameters, highlighting their fundamental roles in groundwater recharge processes. This study emphasizes the robustness and applicability of integrating AHP with GIS for sustainable groundwater resource management, providing practical guidance for resource planning, agricultural development, and water security. By effectively combining expert judgment, statistical consistency, and spatial analysis, this comprehensive methodology provides a reliable, systematic, and scientifically sound framework for groundwater exploration, assessment, planning, and long-term resource management. Limitations include a small validation sample and limited field hydrogeological data, potentially affecting zone precision. Future research should incorporate field validation, temporal fluctuations, and machine learning weighting to boost accuracy.

Authors' Contributions

RNT: Conception/Design and Interpretation of Data, Drafting of Original Draft of Manuscript and Revision. **BS:** Data Collection. Drafting of Figures, Literature Review. **AKM:** Writing-Original Draft, Revision, Data Collection, Literature Review.

Data Availability

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary material. Raw data that support the findings of this study are available from the corresponding author, upon reasonable request.

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Conflict of Interests

The authors have no competing interests.

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