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ASSESSMENT OF GROUNDWATER POTENTIAL ZONE (GWPZ) IN UDAI RIVER BASIN: A CASE STUDY OF NORTHERN SAPURA MOUNTAIN RANGES USING REMOTE SENSING TECHNIQUES

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Abstract:

Identifying potential groundwater reservoirs is a complex endeavor, especially in arid regions, mountainous terrains, and lateritic areas. In recent years, Satellite Remote sensing has emerged as a promising tool for efficient and cost-effective detection of surface and subsurface water resources. This study focused on identifying potential groundwater zones in the drought-susceptible red and Satpura Mountain Ranges (RSMR) of the Udai River basin. This study employed a multi-criteria approach, leveraging remote sensing and geographic information systems, and considered eight factors: Drainage density, Rainfall, Lineament Density, Slope, Elevation, NDWI, NDVI and LULC. The Analytical Hierarchical Process (AHP) was utilized to assign weights to these parameters, and different classes within each parameter were ranked based on their significance for groundwater potential. The analysis categorized various zones of groundwater prospects as high (33.81%), moderate (269.89%), low (310.69%), and Very Low (10.49%). Validation efforts revealed that 79% of the 38 surveyed dug wells in "good" potential zones were perennial, while all 10 dug wells examined in the 'poor' potential zone were non-perennial. These results demonstrate that the current methodology, which combines AHP with enhanced parametrization, offers a more accurate approach for identifying and mapping groundwater potential zones. The findings of this study have significant implications for water resource management in drought-prone regions. By accurately identifying potential groundwater zones, policymakers and water resource managers can make informed decisions regarding water extraction and conservation in the study region.

Keywords: water resources, drought-prone area, water conservation.

Introduction:

Groundwater is a critical natural resource that plays vital roles in sustaining life, supporting ecosystems, and promoting economic development. Its importance is particularly evident in regions facing water scarcity, such as the Satpura Mountains region of India, where many communities struggle with limited groundwater availability. The excessive exploitation of groundwater resources has led to declining water tables, resulting in dry wells and tube wells, which in turn affect the drinking water supply and agricultural activities. The spatial variability of groundwater in both quality and quantity presents challenges for its effective management and utilization. Groundwater serves multiple purposes including drinking water,

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irrigation, forestry, industrial use, and livestock support (Hasanuzzaman et al., 2022). In many countries, particularly those with monsoon climates in Southwest Asia, groundwater becomes crucial during drier months, when direct recharge from rainfall is minimal (Ghosh et al. 2022). Traditional methods of groundwater assessment, such as hydrogeological surveys, are expensive and time-consuming, especially in semi-arid regions with challenging terrain (Jha et al., 2010). However, the advent of modern technologies such as geographical information systems (GIS) and Remote Sensing (RS) has revolutionized the evaluation and mapping of groundwater resources. These technologies offer cost-effective and efficient means of analyzing extensive geospatial datasets and accurately mapping various natural resources, including groundwater (Shekhar and Pandey, 2014). This study examined the complexities of groundwater resource management through an assessment of the Satpura Mountain River to generate thematic layers that influence groundwater potential and recharge zone formation. The primary objective of this study is to identify and delineate suitable areas for groundwater potential and recharge by integrating these thematic layers. The findings demonstrate the efficacy of combining geographic information system (GIS) and Remote Sensing (RS) technologies with the Analytic Hierarchy Process (AHP) methodology to map groundwater potential and recharge zones.

A comprehensive investigation of groundwater potential zones in Akkalkuwa and Dhadgaon tahsil was conducted utilizing an integrated approach of remote sensing and Geographic Information System (GIS) techniques. This research, undertaken in the Northern Satpura Mountain Range of the Udai River Basin, focused on the hard-rock terrain of the area. Hydrogeomorphology, slope, and drainage density were the primary parameters employed to identify groundwater potential. There is limited research incorporating an integrated approach for identifying Groundwater Potential Zones (GWPZs) in the Udai River Basin. This study concentrates on the Udai River watershed, where the delineation of groundwater potential and recharge zones will provide valuable information for various stakeholders. This information will contribute to sustainable planning, development, and management of groundwater resources, benefiting agricultural irrigation, domestic water supply, and overall water resource management in the study region. This study investigates groundwater potential in Akkalkuwa and Dhadgaon, two specific areas in a mountainous, hard rock region. The researchers employed advanced mapping techniques to analyze three key factors: geomorphology, slope, and drainage density. This approach is novel for this particular river basin. The study's findings may have significant implications for local water resource management strategies, potentially improving access to potable water for communities in these areas. By identifying areas with high groundwater potential, policymakers and water resource managers can make more informed decisions regarding the allocation of resources for well drilling and water infrastructure development. Furthermore, this research methodology could serve as a model for similar studies in other mountain regions, contributing to a broader understanding of groundwater dynamics in challenging geological environments.

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Study Region:

Located within the Satpura Mountain ranges, the Udai River basin is a tributary system of the Narmada River. It is situated between 21°36′ 00″ N and 22°′0 ′ latitude, and 74°0′ E and 74°24 0″ E longitude (fig.01). The Udai River, which is the longest tributary of the Narmada River, has a basin area of 624.88 km^2, encompassing portions of northern Nandurbar District in Maharashtra, India. The river begins at the Upper Dab (Hello Dab) at an elevation of 733 m and flows for 49.8 km through a narrow, deep channel in a southwest to northeast direction.

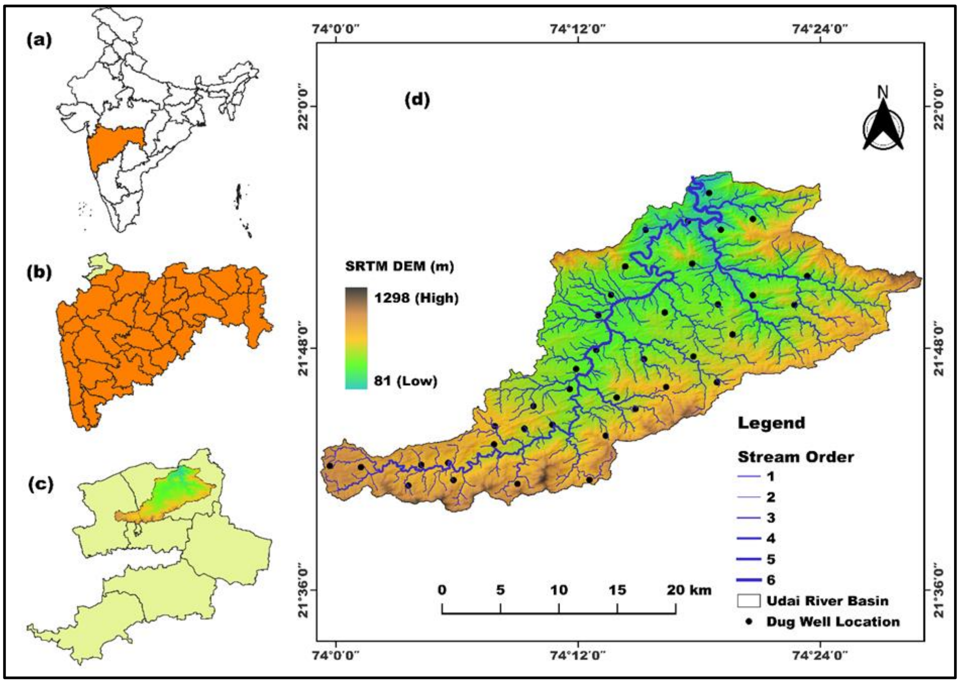

Fig.01. Location Map of Study Area in (a) India, (b) Maharashtra, (c) Nandurbar District, and (d) the Udai River Basin.

The basin is known for its varied topography, featuring sudden changes in gradient and significant variations in terrain relief. The region experiences a subtropical climate, with summer temperatures peaking between 30 and 42°C and winter temperatures dropping to between 3 and 10 °C at their lowest. The area receives annual rainfall ranging from 928 to 1261 mm, which occurs during monsoon seasons. The land surface of the area is characterized by hard rock uplands, undulating laterite and black soil area. The hard rock uplands consist primarily of granite and gneiss formations that contribute to the rugged terrain of the river basin.

Objectives:

1. To study physiographic situation of Udai River basin in Satpura Mountain ranges.
2. To Find out the dug well location of the Udai River basin.
3. To investigate the groundwater recharge potential zone of Udai River Basin.

Data Based and Research Methodology:

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The processes used to delineate groundwater potential zones are listed in Table 1. Eight thematic layers (Rainfall, Drainage Density, Lineament density, slope, elevation, NDWI, NDVI, and LULC) significantly controlled the groundwater availability. GWPZs were acquired by superimposing all thematic layers using the weighted overlay technique with a spatial analysis tool in ArcGIS 10.4.1. The groundwater potential zone (GWPZ) was defined using these parameters. Groundwater potential was mapped using GIS, AHP, weightage, and remote sensing methods. The parameters were analysed using the AHP approach, and their rating coefficients were derived. Groundwater potential mapping was performed, and the groundwater potential zone was evaluated using parameter ratings and weights. The study area was prepared using SRTM DEM (30 m spatial resolution), obtained from the USGS website 'http://earthexplorer.usgs.gov/ using Arc GIS 10.1.4. The SRTM DEM raster generated factors including drainage density, slope, and elevation. LANDSAT-8 (OLI/TIRS) data was acquired from the USGS Earth Explorer website 'https://earthexplorer.usgs.gov' and processed using Arc GIS 10.4.1. The level-2 data underwent radiometric correction before creating the NDVI, NDWI, and LULC thematic layers. Annual rainfall data (2022) was obtained from https://www.imdpune.gov.in. Groundwater depth data for analysis. The lineament density parameters were derived from the Bhukosh GSI data website 'https://bhukosh.gsi.gov.in.' Land use and land cover (LULC) information was downloaded from Landsat 8 satellite data (30m spatial resolution). All assigned layers were resampled into a 30 m raster dataset, and three AHP models were used to finalize the groundwater potential zone analysis. Thematic layers were integrated using a weighted overlay technique to generate the final groundwater potential zone map and were classified into four categories: high, moderate, low, and very low potential. The results can be used by water resource managers and policymakers to identify areas suitable for groundwater development and to implement sustainable water management strategies.

Assigning Rank and Weight:

The assessment of groundwater potential zones involved integration of all spatial layers using a weighted overlay method. Each layer was normalized to a 1–5 scale, with 1 signifying low groundwater potential and 5 signifying excellent groundwater potential. An AHP-based pairwise comparison matrix (Table 1) was used for weight allocation. Parameter rankings were based on field observations, stakeholder inputs, expert surveys, and relevant studies (Krishnamurthy et al. 1996; Saraf and Choudhury, 1998; Waikar and Nilawar, 2014). Rainfall received the highest weight, whereas Drainage density, lineament density, and Slope were assigned moderate weights. Land use/cover was assigned a low weight (Table 02). Following the parameter weight assignment, individual ranks were designated as subvariables (Butler et al. 2002; Asadi et al. 2007; Yammani 2007). The highest value corresponds to the greatest groundwater potential, whereas the lowest indicates the lowest potential.

Table 01: Normalized Pairwise comparison matrix (Eight Layer) developed for AHP based Groundwater potential zone.

Parameters	RF	DD	LD	SP	EV	NDWI	NDVI	LULC	Weight (W)

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Rainfall (RF)	8	7	6	5	4	3	2	1	0.36
Drainage Density (DD)	8/2	7/2	6/2	5/2	4/2	3/2	2/2	1/2	0.18
Lineament Density (LD)	8/3	7/3	6/3	5/3	4/3	3/3	2/3	1/3	0.12
Slope (SP)	8/4	7/4	6/4	5/4	4/4	3/4	2/4	1/4	0.09
Elevation (EV)	8/5	7/5	6/5	5/5	4/5	3/5	3/5	1/5	0.08
NDWI	8/6	7/6	6/6	5/6	4/6	3/6	3/6	1/6	0.06
NDVI	8/7	7/7	6/7	5/7	4/7	3/7	4/7	1/7	0.06
LULC	8/8	7/8	6/8	5/8	4/8	3/8	5/8	1/8	0.05
Total	21.73								1

Source: Computed by researcher in Arc GIS 10.4. Software.

Thematic Layer for Ground Water Potential Zone (GPZ):

1) Rainfall:

In the research area, rainfall is the principal source of groundwater recharge, and it plays an important role in the hydrological cycle. Rainfall nourishes river regions while regulating the groundwater levels. Rainfall is directly responsible for the recharge potential of groundwater as it helps in groundwater storage through the infiltration process. The pace of infiltration is affected by the amount and duration of rainfall. Short-duration, high-intensity rain causes more surface runoff and less infiltration, whereas long-duration, low-intensity rain causes a higher infiltration rate (Adhikary et al. 2018; Bera et al. 2020; I. brahim-Bathis and Ahmed 2016). Rainfall data from 2022 were used in this investigation. The annual rainfall ranges from 928.35 and, 261.3 mm (table no.02 and fig.02,a) The geographical distribution of rainfall was determined using the kriging interpolation method in Arc GIS. The rainfall map was reclassified into five classes: very low (928.35 - 970.13 mm), low (1,026.29 - 1,100.7 mm), moderate (1,100.71 - 1,179.04 mm), high (1477.60–1534.54 mm), and very high (1,179.05 - 1,261.3 mm).

2) Drainage Density:

Drainage density refers to the length of stream channels per unit area within a basin (Horton 1932; Strahler 1952). Various factors, including rock composition, soil characteristics, and terrain steepness, affect the drainage density (Manap et al. 2013). The measurement of drainage density is determined by the spacing between the channels. In a river basin, the drainage density functions inversely to permeability.

$$Dd = \sum_{i=1}^{i=n} \frac{Di}{A} (km^{-1})$$

A higher drainage density leads to increased surface runoff and reduced water infiltration into the ground, whereas the opposite is true (Bera et al. 2019). The Udai River basin's drainage density has been categorized into five groups: very low (0 - 0.61 km/km2), low (0.62 - 1.08 km/km2), moderate (11.09 - 1.52 km/km2), high (1.53 - 1.99 km/km2), and very high (2 - 3.19 km/km2). These categories cover areas of 107.01 km2, 151.78 km2,

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162.64 km2, 138.14 km2, and 65.28 km2, respectively (table, 02 and fig. 02, b). Approximately 41.4 percent of the total area consists of low and very low drainage density zones, which are assigned higher weightage values than zones with high drainage density.

3) Lineament Density (LD):

Lineaments, observable in satellite imagery as linear or curvilinear features on the Earth's surface, indicate underlying geological structures, such as faults, fractures, and cleavages. The calculation of lineament density employs a grid-based approach, in which the total lineament length within a grid is divided by the grid area (Edet et al. 1998). In the Udai River Basin, which is predominantly composed of hard rock, lineaments play a crucial role in creating secondary porosity and permeability that are vital for groundwater replenishment. The main fractures in the study area extended from southwest to northeast.

Table 02: Weights assigned for different groundwater control parameter in the Udai River basin.

Sr. No	Parameters	Class	Wight	Influence	Rank	Area
1	Rainfall	928.35 - 970.13	0.36	36	1	175.90
		970.14 - 1,026.28			2	199.15
		1,026.29 - 1,100.7			3	137.00
		1,100.71 - 1,179.04			4	87.99
		1,179.05 - 1,261.3			5	24.86
2	Drainage Density	0 - 0.61	0.18	18	1	107.01
		0.62 - 1.08			2	151.78
		1.09 - 1.52			3	162.64
		1.53 - 1.99			4	138.14
		2 - 3.19			5	65.28
3	Lineament Density	0 - 25.56	0.12	12	1	307.43
		25.57 - 67.83			2	183.77
		67.84 - 106.17			3	63.70
		106.18 - 156.3			4	51.86
		156.31 - 250.67			5	17.99
4	Slope	0 - 7.41	0.09	09	5	196.72
		7.42 - 14.56			4	178.71
		14.57 - 22.23			3	132.29
		22.24 - 31.76			2	86.19
		31.77 - 67.5			1	30.97
5	Elevation	81 - 335	0.08	08	5	69.88
		335.01 - 488			4	182.07
		488.01 - 647			3	164.62
		647.01 - 834			2	128.34
		834.01 - 1,298			1	79.96

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6	NDWI	-0.44 - -0.23	0.06	06	5	66.86
		-0.22 - -0.18			4	182.74
		-0.17 - -0.13			3	235.24
		-0.12 - -0.05			2	122.29
		-0.04 - 0.16			1	17.76
7	NDVI	-0.14 - 0.08	0.06	06	1	19.89
		0.09 - 0.14			2	180.61
		0.15 - 0.19			3	223.59
		0.2 - 0.25			4	147.13
		0.26 - 0.5			5	53.66
8	LULC	Water Bodies	0.05	05	5	2.60
		Forest			4	2.73
		Agriculture			3	177.43
		Rural Settlement			2	2.63
		Bare Land			1	439.46

Source: Computed by researcher in Arc GIS 10.4. Software.

Lineament density in the region is classified into five main groups: very low (0 - 25.56 km/km2), low (25.57 - 67.83, km/km2), moderately low (67.84 - 106.17 km/km2), high (106.18 - 156.3 km/km2), and very high (156.31 - 250.67 km/km2) (table 2. and fig. 02, c). Areas with high to very high lineament densities are considered promising for groundwater development initiatives

4) Slope:

The slope, a key characteristic of the terrain, represents the inclination of the ground surface. Slope gradient is a crucial terrain feature for assessing groundwater vulnerability and directly influences surface water infiltration. Lower slope angles indicate a flatter terrain, whereas higher values suggest steeper landscapes. At steep inclines, water rapidly flows downward, limiting the time for precipitation to be absorbed, resulting in a reduced recharge potential. Conversely, areas with gentle slopes provide more time for groundwater recharge. Consequently, regions dominated by gentle slopes are more conducive to groundwater replenishment than regions with steep terrains. For this study, a slope map was generated using the SRTM DEM. The slope data were categorized into five classes: flat (0–7.41°), gentle (7.42 - 14.56°), medium (14.57 - 22.23°), steep (22.24 - 31.76°), and very steep (> 67.5°) (Fig. 02, d).

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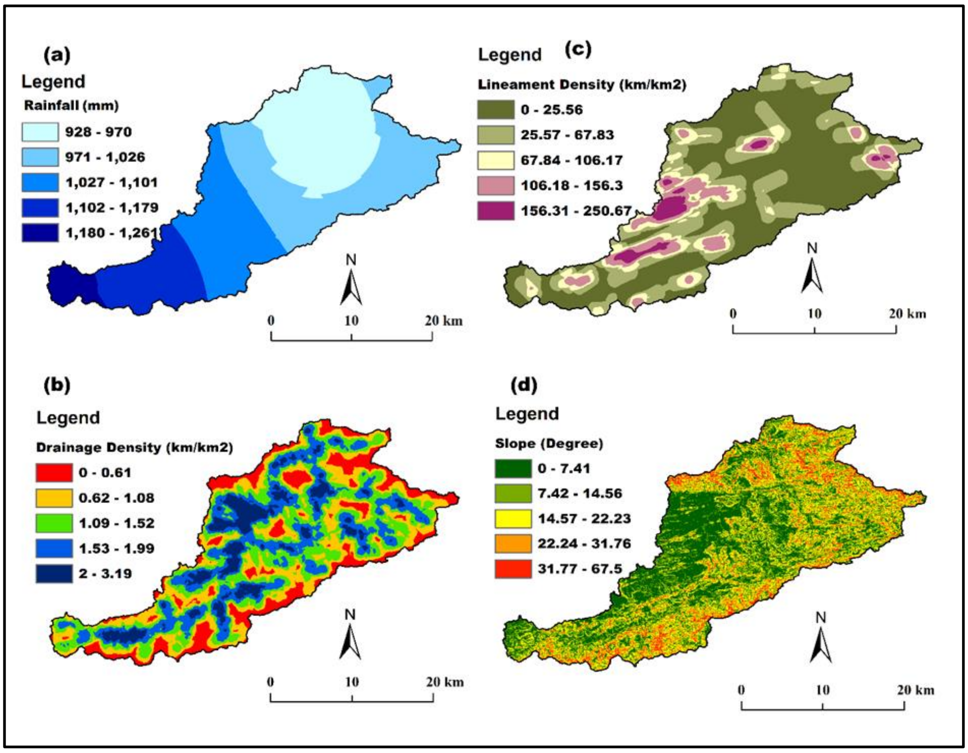

Fig.02. Thematic map of Groundwater Potential Zone in (a) Rainfall, (b) Drainage Density, (c) Lineament Density and (d) Slope.

5) Elevation:

The stream gradient, which is crucial for determining the groundwater potential in a drainage basin across altitude variations per unit area, is significantly influenced by elevation (Patra et al. 2018; Das and Pal, 2020). In the current study area, the elevation range has been categorized into five distinct classes: above 81 – 335 m, 335.01 - 488m, 488.01 – 647 m, 647.01 - 834m, and 834.01 - 1,298 m (Fig. 03, e). The elevation of the basin spans 81–1298 m. In the upper basin, where altitudes are high and infiltration capacity is limited, low groundwater concentrations are found between 647.01 and 834 m above mean sea level (msl). Conversely, the lower basin exhibits maximum concentrations ranging from 81 to 335 m (msl) owing to extensive water logging and a reduced gradient ratio (CGWB 2014). Consequently, different weighting values were allocated to various elevation levels.

6) Normalized Differences Water Index (NDWI):

The Normalized Difference Water Index (NDWI) is frequently used to detect water bodies and evaluate moisture content in vegetation and earth. The calculation of NDWI typically involves a formula using the green and Short-Wave Infrared (SWIR) bands. In this study, lower NDWI values were considered unfavourable, whereas higher values were deemed favourable. The study employed LANDSAT 8 imagery, applying equation to generate an NDWI map (Fig. 03, f) for Udai River basin.

$$NDWI = (Green - NWIR)/ (Green + NWIR)$$

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This map is categorized into five distinct subclasses: (-0.44 to -0.23), (-0.22 to -0.18), (-0.17 to -0.13), (-0.12 to -0.05), and (-0.04 to 0.16).

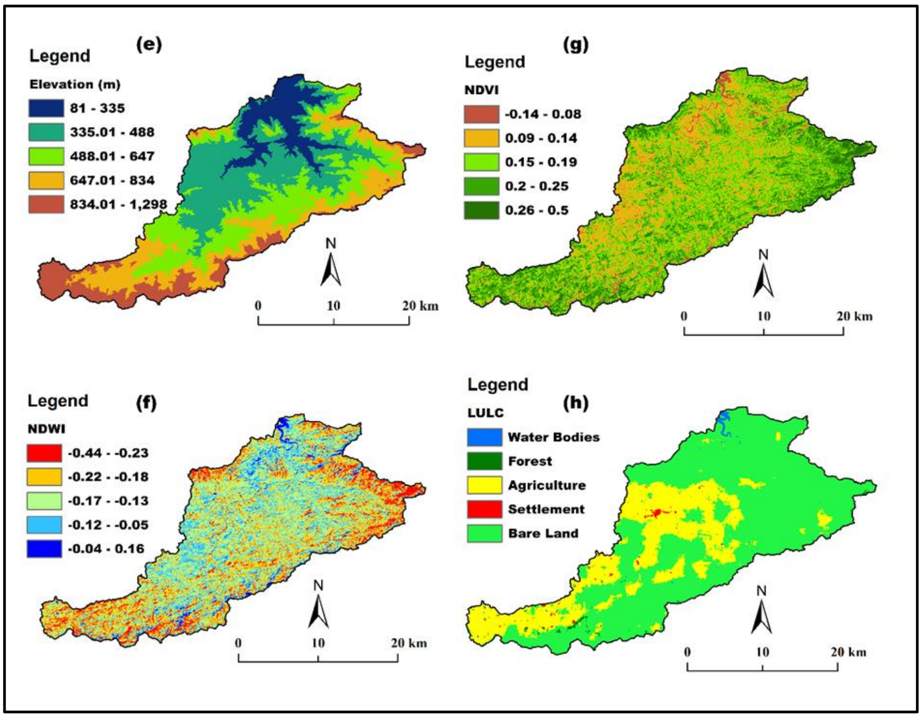

Fig.03. Thematic map of Groundwater Potential Zone in (e) Elevation, (f) NDWI, (g) NDVI and (h) LULC.

7) Normalized Differences Vegetation Index NDVI:

The Normalized Difference Vegetation Index (NDVI) serves as a technique for evaluating groundwater potential in specific regions by measuring the health and density of vegetation. Areas exhibiting high NDVI values may suggest greater groundwater availability, as robust plant growth often depends on accessible subsurface water resources. Conversely, locations with lower NDVI readings might indicate limited groundwater presence, rendering them less favourable for water exploration initiatives. This study employed a LANDSAT 8 image and applied a particular equation to generate the NDVI map (table,2 and fig.3, g) of the Udai River Basin.

$$NDVI = (NIR - Red)/ (NIR + Red)$$

8) Land Use and Land Cover (LULC):

The LULC plays a crucial role in determining the distribution and availability of groundwater in any given area. Moreover, LULC can be considered a key factor in regulating groundwater recharge processes as it provides essential data on infiltration, soil moisture levels, subsurface demand, and reliance on surface water in a particular region (Rana et al., 2022). The LULC map (Fig.3, h) was created using supervised image classification techniques in Arc GIS 10.4.1 software, utilizing satellite imagery from Landsat 8. (fig.02,h).

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Result and Discussion:

The groundwater potential zones of the Udai River Basin (GPZ) were identified by combining weighted factors such as Rainfall, Drainage Density, Lineament density, slope, Elevation, NDWI, NDVI, and LULC. This was done using the Arc GIS 10.4.1 spatial analysis tool and by applying the AHP and GIS methods. Multi-criteria evaluation through overlay analysis involves ranking individual factors and weighting subfactors based on their impact on the criterion (Barik et al. 2016). The GPZ of the Udai River Basin was categorized into four groups: very low (1.68 percent), low (49.72 percent), moderate (43.19 percent), and high (5.41 percent) (Fig. 04, and table, 03).

Table No.03 Groundwater Potential Zone (GWPZ) of Udai River Basin in Satpura Mountain Ranges.

Sr. No	Groundwater Potential Zone	Area in Sq.km	Area in %
1	Very Low	10.49	1.68
2	Low	310.69	49.72
3	Moderate	269.89	43.19
4	High	33.81	5.41
	Total	624.88	100

Computed by researcher in Arc GIS 10.4. Software.

The study revealed that the main GPZ was situated in the upper and central parts of the river basin, particularly in tribal villages, such as Dab, Todikund, Khodi, Chivaltar, Umraghvan, Ambaribar, Jamana, Orpa within the Satpura ranges. This is due to the high rainfall intensity, lineament presence, steep and gentle slopes, extensive agricultural land, and dense forest with superior infiltration capacity. The southeastern basin receives the highest amount of rainfall. The northeastern study area, including Nimkhedi, Savaryadigar, Bilgaon, Trishul, Telkhedi, and Selkuvi, shows poor or low potential because of poorly drained soil and underlying fine-grained basaltic hard rock that hinders groundwater recharge. Elevation, slope, land cover, and forest type were the primary factors influencing the groundwater potential in this region. In the current context of high groundwater demand, identifying potential groundwater zones is crucial as it allows for reconsideration and further improvement from a resource perspective. Consequently, mapping potential groundwater zones in the Udai River Basin provides regional planners with insights into optimal water management and contributes to sustainable development. The outcomes of this study offer valuable information for water resource management in the Udai River Basin. These findings can help prioritize areas for groundwater conservation and development. Additionally, the methodology used in this study can be applied to other river basins to evaluate the groundwater potential and guide sustainable water management strategies.

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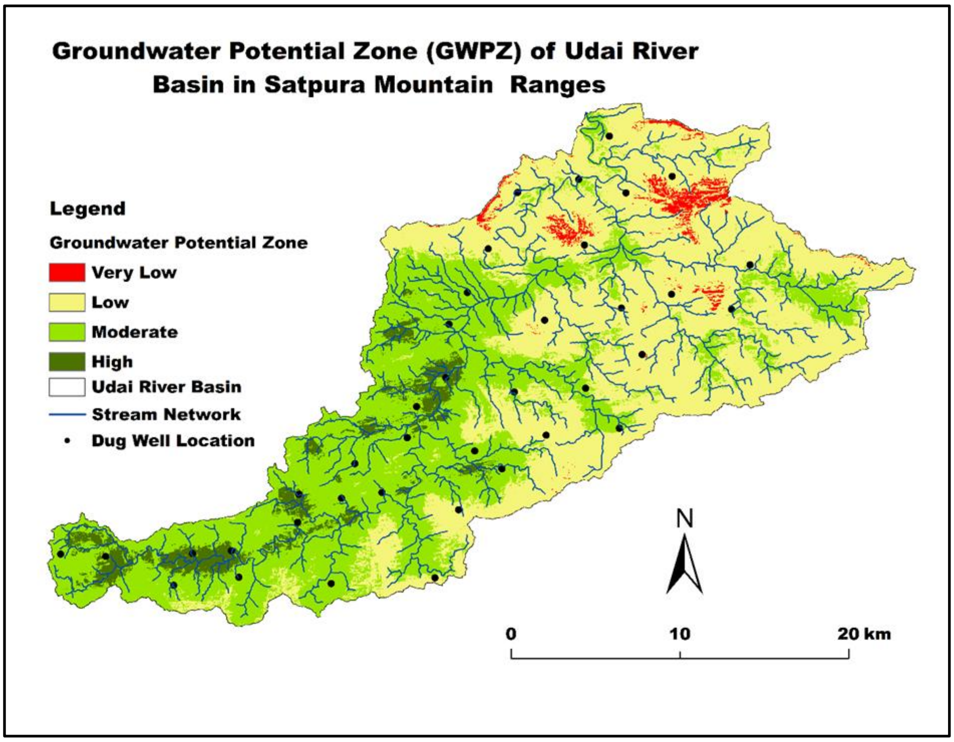

Fig.04 Groundwater Potential Zone (GWPZ) of Udai River Basin in Satpura Mountain Ranges.

Conclusion:

The groundwater potential zones of the Udai River Basin were successfully identified through the integration of AHP methodology with remote sensing and GIS techniques. The analysis indicated that 5.41% and 43.19% of the study area exhibited high and extremely high groundwater potential, respectively. This study examined the relationship between groundwater occurrence and various environmental factors such as precipitation, drainage patterns, lineament density, topography, elevation, NDWI, NDVI, and land use/land cover. This research also evaluated the effectiveness of the AHP approach in locating groundwater potential zones using Ground Control Points (GCP). By adopting a systematic and quantitative approach, this study provides valuable insights for groundwater resource management. Given the increasing scarcity of resources, the resulting groundwater potential map is a crucial tool for policymakers in urban planning and water resource administration. The accuracy of the methodology was verified through pre- and post-monsoon groundwater depth measurements, thereby confirming its reliability. The application of remote sensing and GIS-based multi-criteria evaluation (MCE) has proven to be a reliable and efficient method for groundwater potential mapping. These findings provide a valuable resource for policymakers, water resource planners, and local authorities to support sustainable groundwater management and conservation strategies. To enhance accuracy, future research should incorporate hydrogeological field validation and groundwater quality assessments. This study underscores the significance of geospatial analysis in groundwater exploration, offering a framework that can be applied to other hydrologically important regions for effective water resource management.

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