International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
IJABR 2024; SP-8(12): 164-175
www.biochemjournal.com
Received: 13-08-2024
Accepted: 14-09-2024

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Identification of ground water potential zones for Mula river basin using RS and GIS techniques

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DOI: https://doi.org/10.33545/26174693.2024.v8.i12Sc.3093

Abstract
Groundwater serves as a vital source of fresh water for both rural and urban populations. With increasing global water demand due to population growth and industrial needs, managing water resources sustainably is crucial, especially in arid and semi-arid regions. This study identifies the groundwater potential zones in the Mula River basin of Ahmednagar district (Maharashtra), using Remote Sensing (RS), Geographic Information System (GIS) and Multi-Criteria Decision Analysis (MCDA), specifically the Analytical Hierarchy Process (AHP) techniques. The study area covering of 2570.73 km², different data sets were collected for the study area for generation of different thematic layers, this generated thematic layers were used for identification of ground water potential zones, using Saaty's AHP scale the weights were assigned to different thematic layers as per the influence on groundwater potential and consistency of weights were checked using AHP techniques. The resulting groundwater potential map categorized the basin into four zones: excellent, good, moderate and poor. The results show that 26.99 km^2 (1.05%) have excellent groundwater potential, 1287.16 km^2 (50.07%) have good potential, 843.71 km^2 (32.82%) have moderate potential, and 412.86 km^2 (16.06%) have poor groundwater potential. The ground water potential zones corresponding to the recharge depths of groundwater well data were validated for 25 groundwater well of study area. It was observed that the number of wells in the poor, moderate, good and excellent potential zones were 2, 9, 5 and 9 respectively. This study also highlights the RS, GIS, and AHP techniques were effective tools for sustainable groundwater management.

Keywords: Groundwater recharge, zones, remote sensing, GIS, AHP

Introduction

The rapidly growing global population, which increased from 6.05 billion in 1999 to 8.1 billion in 2022 (USAID, 2023), poses major challenges in managing natural resources. As demand for food and fiber rises, the pressure on land and water resources grows, leading to reduced soil productivity and water availability. India, home to 17.5% of the world's population, is projected to become the most populated country by 2050 with approximately 1.69 billion people (Anonymous, 2015) [2]. With only 328 million hectares of land, India faces shrinking cultivable land due to industrialization and urbanization, increasing strain on its resources to meet food demands.

Water, essential for social and economic progress, is heavily impacted by population growth and climate change. Despite covering over two-thirds of earth, accessible fresh water is limited to lakes, rivers, and aquifers. This scarcity is felt acutely in arid and semi-arid regions, which face water stress or scarcity. Sustainable management of water resources is essential to ensure availability for current and future needs (Rao and Raju, 2010) [8]. Effective water use is crucial to maintain balance within natural water cycles and support economic and environmental stability. As water scarcity intensifies globally, groundwater remains a crucial yet limited resource, essential for human health, agriculture, and economic stability. According to the Central Ground Water Board (2023), India's annual replenishable groundwater is 449.08 BCM, with a net available supply of 407.21 BCM and 241.34 BCM used annually, marking a 59.26% development stage. Increased demand from population growth, agriculture, and industrialization has accelerated groundwater extraction, especially in semi-arid and hard rock regions where overuse causes wells to dry, impacting productivity.

Efficient groundwater management is vital, particularly for India's Mula River basin in Ahmednagar district of Maharashtra which relies heavily on groundwater for agriculture and daily needs. Using integrated Remote Sensing (RS), Geographic Information System (GIS), and Multi-Criteria Decision Analysis (MCDA), specifically the Analytical Hierarchy Process (AHP) approach, this study aims to identify groundwater potential zones. RS and GIS enable hydro-geomorphological mapping, while AHP aids in decision-making through pairwise comparison of various criteria. In the view of above stated points, the study was taken to identification and delineation of ground water potential zones using RS and GIS techniques for Mula River Basin of Ahmednagar district using overlay analysis of spatial and non-spatial data.

Materials and Methods

Study area

The Mula River basin of Ahmednagar district is geographically located between 19° 2′ 24″ to 19° 31′ 48″ North latitude and 74° 0′ 5″ to 74° 50′ 13″ East longitude. The area of basin is 2570.73 km². The elevation ranges from 408 m to 1095 m above mean sea level. The slope of the study area is from South-West to North-East. The study area is occupied by the 'Deccan Basalt/Traps'. The location map of the study area with respect to Maharashtra and India is shown in Fig. 1. Climatic condition of study area is generally hot and dry with average annual rainfall of 566 mm. The temperature typically varies from 12°C to 37 °C and is rarely below 9 °C or above 40 °C. The wind blows mainly from the west, with an average speed of 3.5 m/s and maximum speed of around 10 m/s. The average relative humidity is around 58%, with a range of 14.7% to 97.5%.

Data acquisition

Following different data sets were collected for the study area for generation of different thematic layers.

- Survey of India (SOI) Toposheets (1:50,000): Nine toposheets of E43C3, E43C4, E43C7, E43C8, E43C11, E43C12, E43C14, E43C15, E43C16 were collected from Survey of India, Pune.
- Geology map was downloaded from Bhukosh Portal of http://bhukosh.gsi.gov.on, Geological Survey of India.
- Soil depth map collected from National Bureau of Soil Survey & Land Use Planning (NBSS&LUP), Nagpur.
- Geomorphology map was downloaded from Bhukosh Portal of http://bhukosh.gsi.gov.on, Geological Survey of India.
- ASTER-GEO-DEM was downloaded from United States Geological Survey's (USGS) official website www.earthexplorer.usgs.gov.
- Land use Land cover: The Sentinel-2 data was downloaded from Environmental System Research Institute (ESRI), http://livingatlas.arcgis.com.
- Groundwater level data for the year 2023 were collected from Groundwater Survey and Development Agency, Ahmednagar.

Software used and their Sources

The software ArcGIS (10.8) and Google Earth Pro were used for the processing of the images and raster data obtained from satellite. ArcGIS (10.8) version was used for the preparation of various thematic maps and also for identifying the groundwater potential zones of the study area. Google Earth Pro was used to superimpose the toposheets and the raster data of the study area.

Weight assignment using Analytical Hierarchical Process (AHP) and normalization: The AHP is a subunit of MCDA method. The GIS based multi criteria assessment applies to define the rates of various classes of each layer. Weights of each thematic layer were allocated according to rating scale of Saaty's AHP method as per the influence on groundwater potential. The Saaty's AHP process introduced by Thomas Saaty in the year of 1980, which is an effective tool for dealing with complex decision making, and may aid the decision maker to set priorities and make the best decision. The AHP considers a set of evaluation criteria, and a set of alternative options among which the best decision is to be made. The AHP generates a weight for each evaluation criterion according to the decision maker's pairwise comparisons of the criteria. The higher the weight, the more important the corresponding criterion. Next, for a fixed criterion, the AHP assigns a score to each option according to the decision maker's pairwise comparisons of the options based on that criterion.

Finally, the AHP combines the criteria weights and the options scores, thus determining a global score for each option, and a consequent ranking. The global score for a given option is a weighted sum of the scores it obtained with respect to all the criteria. The Table 1 shows the procedure of assigning weightage for each parameter and classes with in the parameter based on the importance of it. The value 9 in the table shows higher important, while 1/9 shows the least important while 1 shows the equal weight of a parameter or a class. Based on these weightage criteria each parameter in the study has been classified.

Calculation of the approximate weights by using AHP technique: Analytic Hierarchy Process (AHP) method allows us to determine the weights (ωi) (significances) of hierarchically non-structured or particular hierarchical level criteria in respect of those belonging to a higher level and assessing the consistency of questionnaires elicited from experts. In Saaty's AHP, a comparison of considered criteria of '*n*' numbers to be done (in the study, nine thematic layers i.e. LULC, Geology, Soil, Geomorphology, Drainage density, Lineament density, Elevation, Slope, Groundwater level) and a square matrix was developed. The obtained square matrix normalized through the pairwise comparison matrix. The method is based on the pairwise comparison matrix $P = \| p_{ij} \|$ (i, j = 1, 2, …, n). Experts compare all the evaluation criteria R_i and R_j (i, j = 1, 2, …, m), where n is the number of the criteria compared. In an ideal case, the elements of the matrix present the relationships between the unknown criteria weights:

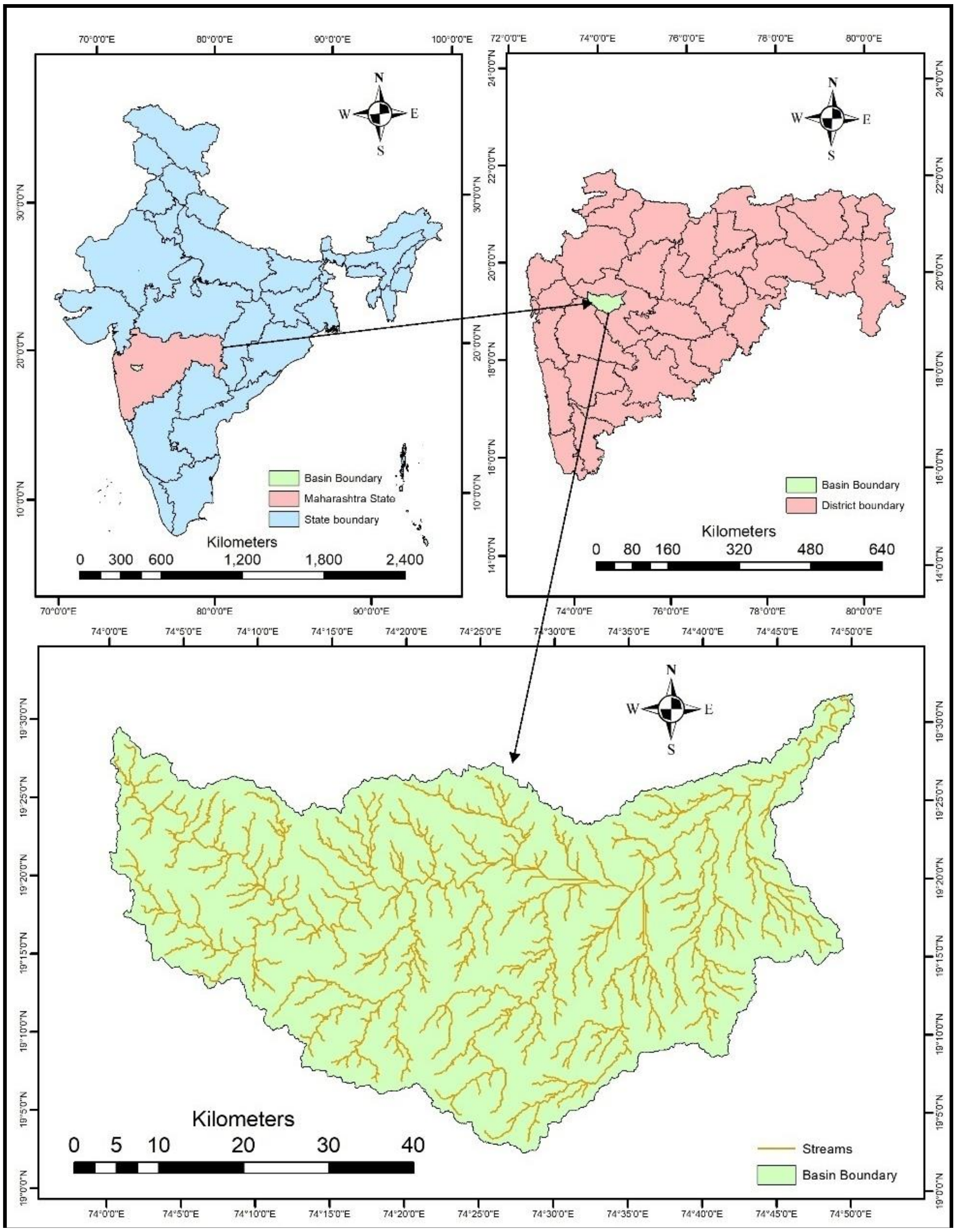

Fig 1: Location map of study area

Table 1: Continuous rating scale of Saaty's Analytical Hierarchical Process

1/9	**1/7**	**1/5**	**1/3**	**1**	**3**	**5**	**7**	**9**
Extremely	Very Strong	Strongly	Moderately	Equally	Moderately	Strongly	Very Strong	Extremely
Less Important ←				Equally	More Important →			
Source: Saaty (1980) [10]	Note:1/8,1/6,1/2,2,4,6,8 can also be used if more number of classes Exit							

$$P = \begin{pmatrix} p_{11} & p_{12} & p_{1m} \\ p_{21} & p_{22} & p_{2m} \\ p_{31} & p_{32} & p_{3m} \\ . & . & . \\ . & . & . \\ p_{m1} & p_{m2} & p_{mm} \end{pmatrix} = \begin{pmatrix} \omega_1/\omega_1 & \omega_1/\omega_2 & \omega_1/\omega_3 \\ \omega_2/\omega_1 & \omega_2/\omega_2 & \omega_2/\omega_3 \\ \omega_3/\omega_1 & \omega_3/\omega_2 & \omega_3/\omega_3 \\ . & . & . \\ . & . & . \\ \omega_m/\omega_1 & \omega_m/\omega_2 & \omega_m/\omega_m \end{pmatrix} = P_\omega$$

The comparison is qualitative and easy to perform. It indicates if one criterion is more signify can't than the other and to what level the priority belongs. The technique used allows the qualitative estimates elicited from experts to be converted to quantitative ones. The main principle of filling in the matrix is simple because an expert should indicate how much more important is a particular criterion than another. Saaty suggested a widely known 5- point scale (1-3-5-7-9) to be used for evaluation. The evaluation of the criteria ranges from p_{ij} = 1, when R_i and R_j are equally significant, to p_{ij} = 9, when the criterion R_i is much more significant than the criterion R_j with respect to the research aim (Saaty 1980) [10].

In an ideal case, inverse symmetry of matrix P is evident: for example, if one object is five times as heavy as another, then, the latter is 1/5 as heavy as the first object. In this case, the elements of any two matrix columns or rows will be proportional. This means that the relationships between the elements of the respective columns will be the same. For example, the relationships between the elements of the first and second columns are as follows:

$$\frac{Pi1}{Pi2} = \frac{\frac{\omega i}{\omega 1}}{\frac{\omega i}{\omega 2}} = \frac{\omega 2}{\omega 1} \text{ (i = 1,2,3…., n)}$$

The formulae given in Table no. 2 were used to check the consistency of weightages assigned to the different thematic layers. The normalized matrix is created from the pair-wise comparison matrix by first summing up all the values in each column of the comparison matrix. Then, each value in the matrix is divided by the sum of its respective column. This process ensures that the sum of all values in each column of the normalized matrix equals one. The Eigen vector is then calculated by taking the average of all the values in each row of the normalized matrix.

Table 2: Parameters of AHP to check consistency of weightages assigned to thematic layers

AHP parameters	Formula	Remarks
Consistency Measures	(Row of comparison Matrix) × (Eigen Vector) / Corresponding Eigen Vector of the row	Last column of the Normalized Matrix
Principal Eigen Value	λmax	Average of the column of Consistency Measures
Consistency Index (CI)	$\frac{\lambda max - n}{n-1}$	*n* is number of thematic layers
Consistency Ratio (CR)	$\frac{CI}{RI}$	RI is Random Index from Table 3

A significant problem is to ensure the consistency of the matrix. The matrix P is consistent if from the minimal amount of its elements all other elements can be obtained. The elements of the columns (and rows) of a consistent matrix will be proportional.

The judgment of uncertainty is based on Saaty's Consistency Index (CI). The smaller the consistency index, the higher the consistency of the matrix. In the ideal case, CI = 0. In fact, the ideally consistent matrix is a rare case, even if transitivity of its elements has been checked. The consistency degree of matrix P may be determined quantitatively by comparing the calculated consistency index of the matrix with a randomly generated consistency index (based on the scale 1-3-5-7-9) of the inverse symmetrical matrix of the same order.

The measurement of Consistency Ratio (CR) is a pairwise comparison matrix, which is calculated with the following equation.

$$Consistency\ Ratio = \frac{CI}{RI} \text{ ………(1)}$$

Where,
CI = Consistency Index and
RI = Random Index

The RI values representing for different numbers of *n* are shown in Table 3 (Saaty,1980) [10]. Inverse second-order symmetrical matrices are always consistent. The relationship between the calculated Consistency Index CI of a particular matrix and the average Random Index value CR is referred to as consistency relationship. Table 3 shows values of Random Index (RI) for the determine consistency ratio (Saaty 1980) [10] and it determines the degree of matrix consistency:

Table 3: Values of Random Index (RI) for number of thematic layers (*n*)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

The value of consistency ratio (CR) which is smaller than or equal to 0.1 is acceptable, implying that the matrix is consistent. (Saaty, 1987) [9]. If CR values deviate from the stated condition, re-evaluation of corresponding weights should be practiced avoiding inconsistency, otherwise the AHP may provide faulty results.

Identification of groundwater potential zones

The detailed methodology for the identification and delineation of GWPZ using RS, GIS and AHP tools is depicted in Fig. 2

The different thematic layers on geomorphology, geology, soil, slope, elevation, drainage density, lineament density, land use land cover and ground water level analysis were used for the delineation of groundwater potential zones in the study area. To demarcate potential zones, all these thematic layers were integrated (overlay) using Modeler tools in Arc GIS 10.8 software. The weights of different themes were assigned on a scale of 1 to 1/9 based on their influence on the groundwater potential. Different features of each theme were assigned weights on a scale of 0 to 100 according to their influence on groundwater potential. The weights were then finalized considering the weights suggested by various experts and the weights used in earlier studies as well as from local experience. Thereafter, a pairwise comparison of the option based on the criterion using the Saaty's Analytical Hierarchy Process (AHP) to calculate normalized weights for individual themes. Integration of the selected thematic layer/maps for delineation of GWPZ using following equation has been completed in the GIS environment.

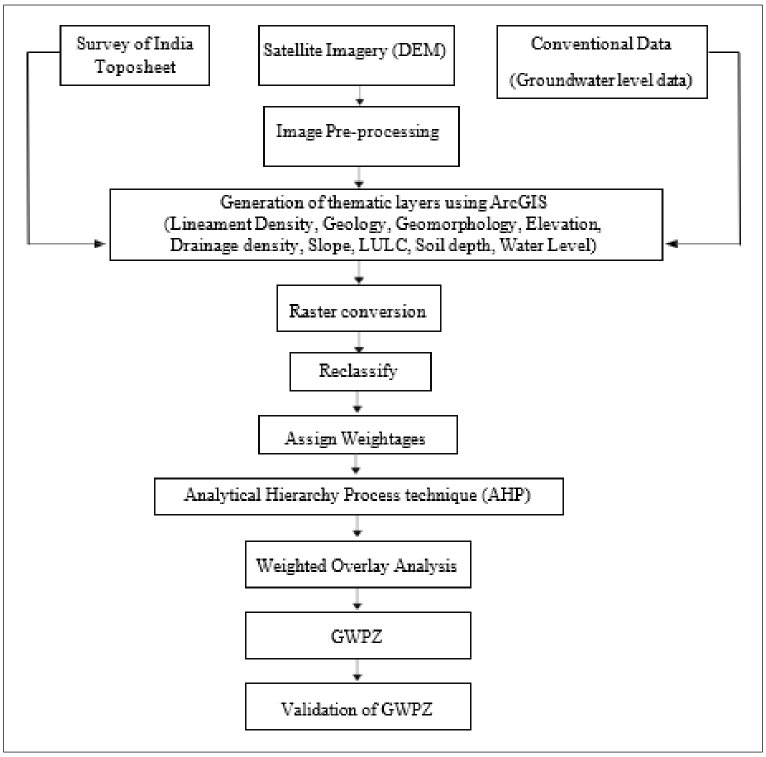

Fig 2: Flow Chart of methodology adopted for identification and delineation of GWPZ

$$GWPZ = \sum_{j=1}^{m}\sum_{i=1}^{n}(\sum x_i \times w_j)$$

Where, x_i and w_j are the normalized weights of the i^{th} and j^{th} classes of thematic layers. *m* represents the no. of the thematic layers and *n* represents the counts of whole classes in each thematic layer. Higher values obtained from this method represents the greater potential for groundwater occurrence.

Groundwater Potential Zones = (Geomorphology) x (Weightage) + (Geology) x (Weightage)
+ (Slope) x (Weightage) + (land use land cover) x (Weightage)
+ (Drainage density) x (Weightage) + (Elevation) x (Weightage)
+ (Lineament Density) x (Weightage) + (Soil) x (Weightage)
+ (Ground Water Depth) x (Weightage)

The verification and validation of obtained GWPZ were examined with the map of water fluctuation data of pre and post monsoon well data of 25 wells obtained from GSDA, Ahmednagar.

Results and Discussion

Generation of thematic layers: Nine thematic layers/maps of drainage density, soil depth, elevation, slope, geomorphology, geology, lineament density, groundwater level, and land use land cover were prepared and depicted in Fig. 3 to 13 and weights were assigned depending on their influence on groundwater potential and given in Table No.4.

Drainage density map

Drainage density is the ratio of total stream length of all the orders per unit basin area (Horton, 1945) [6]. Drainage density is significantly correlated with the groundwater recharge i.e. high drainage density indicates a probable recharge zone of groundwater. Table 4 shows the different categories of drainage density while Fig 3 shows the drainage density map of study area. High drainage density (2.20 – 3.40 km/km^2) was found in the North-Eastern and Central East regions of Mula River basin of Ahmednagar district covering 6.17% of total study area.

Elevation map

Water tends to store at lower topography rather than the higher topography. Higher the elevation lesser the ground water potential recharge and vice versa. The study area's altitude varies from 408 to 1095 meters above sea level, indicating considerable relief (Fig 4 and Table 4).

Slope map

The slope of a particular terrain is an important factor in groundwater studies, because it determines the time required for the water to accumulate at a given location. The slope gradient directly influences the infiltration and surface runoff. The lesser the slope, the lesser will be the runoff, and hence infiltration and recharge will be more thereby making a flat terrain more promising for groundwater availability. Slope classes distribution is shown in Table 4. Slope map of study area is shown in Fig 5. The table shows that the Mula River basin has a very gentle slope covering 37.76% of total area and only 0.13% of area has a very steep slope.

Land Use Land Cover Map

Land use refers to "human activities and various uses which are carried out on land." Land cover refers to "vegetation, water bodies, rocks/ soil, artificial cover and others resulting due to transformations." (Pande *et al.*, 2018) [14]. The land use and land cover map of the basin was prepared using Sentinel 2 satellite data (Fig 6). Table 4 shows that the Mula River basin has majority of the area under the Agricultural land covering 49.97% of total study area followed by the Forest having 41.34% of the total area. Only 0.01% of study area has waste-lands.

Geology Map

Geology is one of the vital controlling factors that influence the occurrence and movement of groundwater flow in a particular area. The flow and existence of groundwater depend on porosity and permeability of rocks. Porous and permeability of the geology area refers to the storage and transmitting capacity, which supports the groundwater occurrence. The geological formation of Mula River basin consists of Deccan Traps shown in Fig 7.

Geomorphology Map

Geomorphology is the science of formation of surface landforms (Thornbury, 1986) [15] and has a direct relation with the occurrence and movement of groundwater flow. The geomorphology of a particular area deals with the rock type, soil type, drainage pattern, etc. and hence, geomorphic units and associated features indirectly control the groundwater prospect of an area (Brown, 1996) [3]. Fig 8 shows the Geomorphology map of study area and Table 4 shows the different classes of geomorphology of study area. The geomorphological class majorly found in Mula River basin is Pediment Pedi-plain complex covering almost 64.34% of total area, followed with Moderately dissected plateau with 31.86% of total area.

Soil Depth Map

Soil is a significant parameter for identifying the GWPZ. The influence of soil on groundwater occurrence mainly depends on its retention capacity or texture. Deep soils, due to their greater thickness, exhibited higher permeability, while shallow soils had lower permeability because of their limited thickness. Soil depth map is shown in Fig 9 and Table 4 shows the distribution of soil depth of study area. Majority of the soil in Mula River basin is Moderately Shallow soil (0.25 – 0.5 m) covering 41.89% of total study area, whereas only 4.55% of total study area is Shallow soil with depth ranging from 0.25 to 0.5 m.

Lineament Density Map:

Lineaments are linear or curvilinear structures on the earth surface, it depicts the weaker zone of bed rocks and area considered as secondary aquifer in hard rock regions. Regions with high lineament thickness are useful for groundwater potential zones (Haridas *et al.*, 1998) [5]. Thus, the Lineaments were assumed a significant job in groundwater potential zoning. Fig 10 shows the lineament density map of study area. The highest lineament density was observed in the south-eastern part of Mula River basin with only 2% of total study area.

Groundwater Level Map

The depth of groundwater is defined as the distance from the ground surface to the water table. The Groundwater level (GWL) map for pre-monsoon (Fig 11) and post-monsoon (Fig 12) data of study area was prepared and also the water table column (groundwater recharge) map (Fig 13) was prepared by using the pre-monsoon and post-monsoon data of the study area. The groundwater level depth for pre-monsoon ranged between 5.2 to 8.6 m, whereas for post-monsoon the level was 5.8 to 10 m.

Table 4: Different classes of thematic layers

Sr. No	Thematic layers	Class Intervals	Area (km^2)	Per cent of Total Area
	Drainage Density (km/km^2)	0-0.30	925.97	36.02
		0.31-0.79	637.78	26.21
		0.80-1.49	524.42	20.4
		1.50-2.19	287.92	11.20
		2.20-3.40	158.61	6.17
		Total	2570.73	100
	Geology	Deccan Trap	2570.73	100
		Total	2570.73	100
	Geomorphology	Anthropogenic terrain	0.26	0.01
		Dam and Reservoir	54.24	2.11
		Low Dissected Hills and Valleys	1.29	0.05
		Low Dissected Plateau	9.51	0.37
		Moderately Dissected Plateau	818.03	31.86
		Pediment Pedi plain Complex	1654	64.34
		Waterbodies-Other	32.39	1.26
		Total	2570.73	100
	Land Use Land Cover	Agricultural Land	1284.59	49.97
		Forest	1062.73	41.34
		Water bodies	84.06	3.27
		Built-up	139.07	5.41
		Waste-land	0.25	0.01
		Total	2570.73	100
	Soil Depth	Deep (1 - 1.5)	748.08	29.10
		Moderately shallow (0.5 - 1)	1076.86	41.89
		Shallow (0.25 – 0.5)	116.97	4.55
		Very shallow (< 0.25)	628.80	24.46
		Total	2570.73	100
	Slope (%)	0-1	322.11	12.53
		1-3	972.70	37.76
		3-5	526.99	20.50
		5-10	387.92	15.09
		10-15	151.93	5.91
		15-35	207.97	8.09
		>35	3.34	0.13
		Total	2570.73	100
	Lineament Density (km/km^2)	0 - 0.13	1645.27	64
		0.14 - 0.27	334.19	13
		0.28 - 0.40	385.60	15
		0.41 - 0.53	154.24	06
		0.54 - 0.67	21.41	02
		Total	2570.73	100
	Groundwater level (m)	2.1 – 2.3	1128.30	43.89
		2.4 – 2.6	383.80	14.93
		2.7 – 2.8	256.81	9.99
		2.9 – 3.0	333.42	12.97
		3.1 – 3.3	468.38	18.22
		2.9 – 3.0	333.42	12.97
	Elevation (m)	408-545	825.98	32.13
		546-683	1106.44	43.04
		684-820	564.01	21.94
		821-958	70.44	2.74
		959-1095	3.85	0.15
		Total	2570.73	100

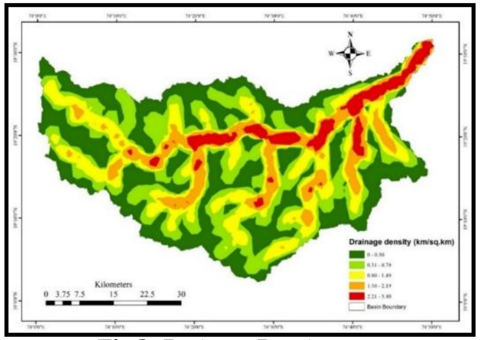

Fig 3: Drainage Density map

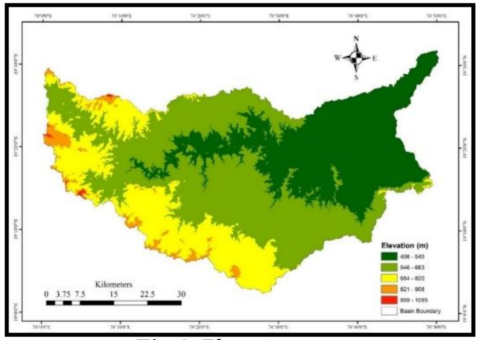

Fig 4: Elevation map

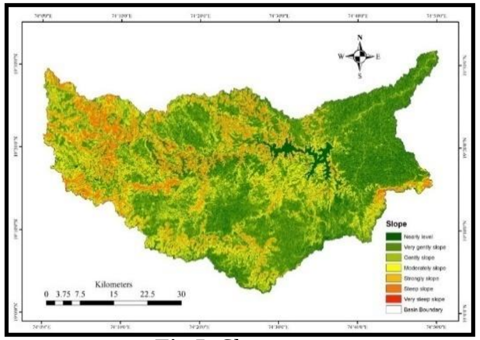

Fig 5: Slope map

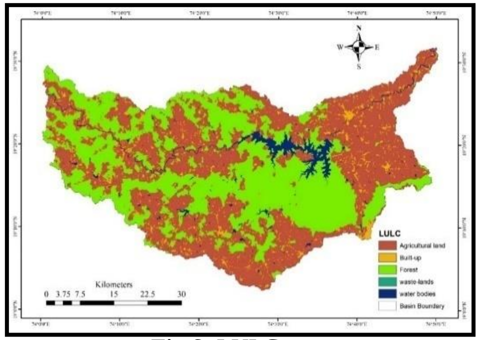

Fig 6: LULC map

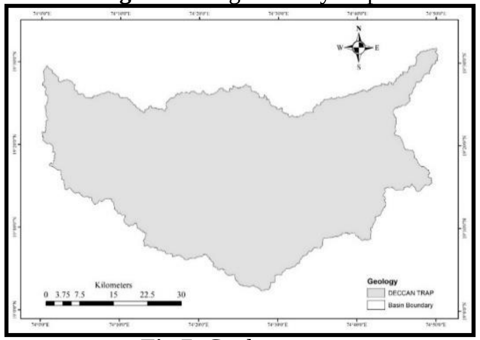

Fig 7: Geology map

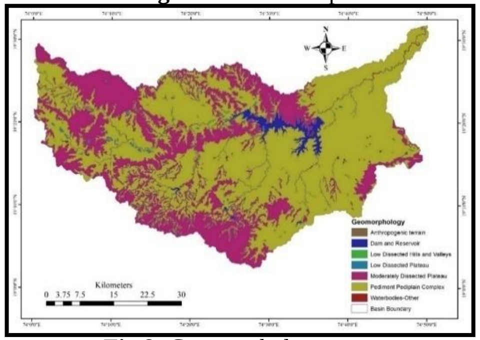

Fig 8: Geomorphology map

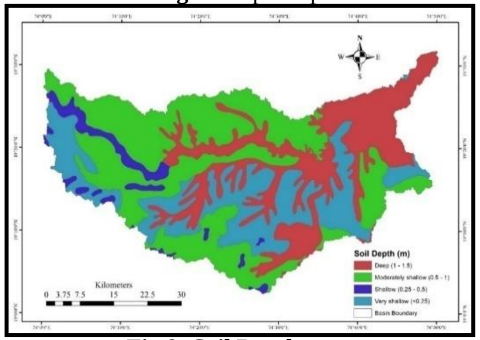

Fig 9: Soil Depth map

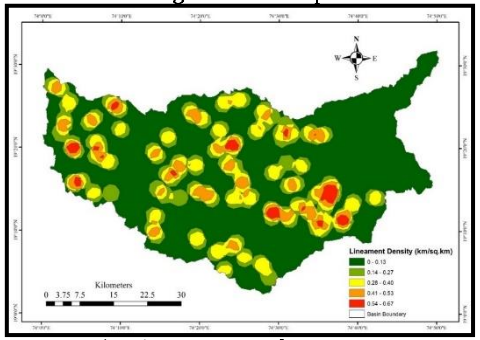

Fig 10: Lineament density map

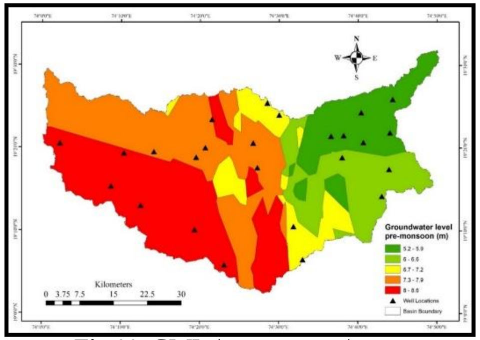

Fig 11: GWL (pre-monsoon) map

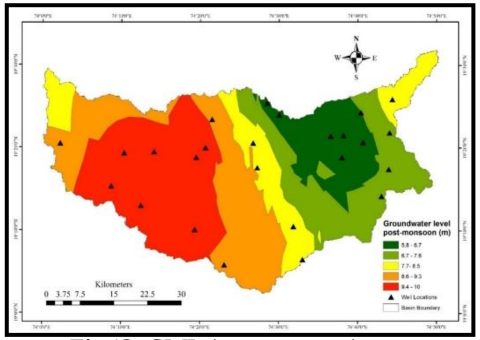

Fig 12: GWL (post-monsoon) map

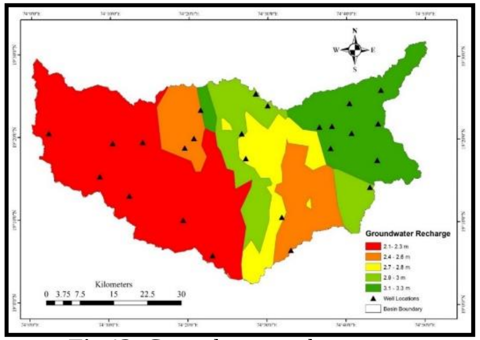

Fig 13: Groundwater recharge map

Identification of Groundwater Potential Zones using AHP method

Weight Assignment for thematic maps:

The weights assigned to different features and themes of the thematic layers for groundwater potential zones were developed based on a review of previous research by experts such as Yonghui An *et al*. (2011), [18] Ramu *et al*. (2014) [7], Vidhya *et al*. (2018) [16], Harsha J *et al*. (2018) [4], Arul Balaji P *et al*. (2019) [1], Narendra V *et al*. (2021), Shinde S *et al*. (2024) [11] as well as the use of the Analytic Hierarchy Process (AHP) developed by Saaty (1980, 1987) [9, 10]. The rating scale from AHP, which was used to assign these weights, is detailed in Table 5

Table 5: Assigned weights of different features of the thematic maps

Sr. No	Influencing Factors	Class Intervals	Groundwater Availability	Saaty Scale (in Frac.)	Saaty Scale (in deci.)	% Influence = (Saaty scale/Sum) *100	Relative Weight
1	Drainage Density (km/km^2)	0-0.30	Very High	1	1	46.08	46
		0.31-0.79	High	1/2	0.5	23.04	23
		0.80-1.49	Moderate	1/3	0.33	15.20	15
		1.50-2.19	Low	1/5	0.2	9.20	9
		2.20-3.40	Very Low	1/7	0.14	6.40	7
		Total			2.17	100	
2	Geology	Deccan Trap	Moderate	1/3	0.33	100	100
		Total			0.33	100	
3	Geomorphology	Pediment Pedi plain Complex	Very High	1	1	37.03	37
		Moderately Dissected Plateau	High	1/2	0.5	18.51	19
		Low Dissected plateau	Moderate	1/3	0.33	12.22	12
		Dams and Reservoirs	Moderate	1/3	0.33	12.22	12
		Waterbodies	Low	1/5	0.2	7.4	8
		Anthropogenic Terrain	Very Low	1/5	0.2	7.4	7
		Low Dissected hills and Valleys	Extreme Low	1/7	0.14	5.18	5
		Total			2.7	100	
4	Land Use Land Cover	Forest	Very High	1	1	46.08	46
		Waterbodies	High	1/2	0.5	23.04	23
		Agricultural land	Moderate	1/3	0.33	15.20	15
		Built-up	Low	1/5	0.2	9.21	9
		Waste Land	Very Low	1/7	0.14	6.45	7
		Total			2.17	100	
5	Soil Depth	Deep	Very High	1	1	49.26	49
		Moderately Shallow	High	1/2	0.5	24.63	25
		Shallow	Moderate	1/3	0.33	16.25	16
		Very Shallow	Low	1/5	0.2	9.8	10
		Total			2.03	100	
6	Slope (%)	0-1	Very High	1	1	38.31	38
		1-3	High	1/2	0.5	19.15	19
		3-5	Moderate	1/3	0.33	12.64	13
		5-10	Moderate	1/3	0.33	12.64	13
		10-15	Low	1/5	.02	7.66	8
		15-35	Very Low	1/7	0.14	5.36	5
		>35	Extreme Low	1/9	0.11	4.21	4
		Total			2.61	100	
7	Lineament Density (km/km^2)	0.54 – 0.67	Very High	1	1	46.08	46
		0.41 – 0.53	High	1/2	0.5	23.04	23
		0.28 – 0.40	Moderate	1/3	0.33	15.20	15
		0.14 – 0.27	Low	1/5	0.2	9.21	9
		0 – 0.13	Very Low	1/7	0.14	6.45	7
		Total			2.17	100	
8	Groundwater level (m)	3.1 – 3.3	Very High	1	1	46.08	46
		2.9 – 3.0	High	1/2	0.5	23.04	23
		2.7 – 2.8	Moderate	1/3	0.33	15.20	15
		2.4 – 2.6	Low	1/5	0.2	9.21	9
		2.1 – 2.3	Very Low	1/7	0.14	6.45	7
		Total			2.17	100	
9	Elevation (m)	408-545	Very High	1	1	46.08	46
		546-683	High	1/2	0.5	23.04	23
		684-820	Moderate	1/3	0.33	15.20	15
		821-958	Low	1/5	0.2	9.21	9
		959-1095	Very Low	1/7	0.14	6.45	7
		Total			2.17	100	

The pair-wise comparison matrix F (n) of above table

$$F(n) = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\ 1/2 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ 1/3 & 1/2 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ 1/4 & 1/3 & 1/2 & 1 & 2 & 3 & 4 & 5 & 6 \\ 1/5 & 1/4 & 1/3 & 1/2 & 1 & 2 & 3 & 4 & 5 \\ 1/6 & 1/5 & 1/4 & 1/3 & 1/2 & 1 & 2 & 3 & 4 \\ 1/7 & 1/6 & 1/5 & 1/4 & 1/3 & 1/2 & 1 & 2 & 3 \\ 1/8 & 1/7 & 1/6 & 1/5 & 1/4 & 1/3 & 1/2 & 1 & 2 \\ 1/9 & 1/8 & 1/7 & 1/6 & 1/5 & 1/4 & 1/3 & 1/2 & 1 \end{pmatrix}$$

The normalized matrix for the present study was obtained from the pairwise comparison matrix. The sum of the normalized records in every column should be one. The eigenvector is calculated as the average of all components in the row. The derived normalized matrix for the present study is presented in Table 6

Table 6: Normalized Matrix

Layers	Geology	LULC	Geomorphology	Slope	Lineament Density	Soil Depth	Elevation	Ground Water level	Drainage Density	Total	Eigen Vector (Average)
Geology	0.35	0.42	0.40	0.35	0.31	0.27	0.24	0.22	0.20	2.76	0.3069
LULC	0.18	0.21	0.26	0.26	0.25	0.23	0.21	0.19	0.18	1.96	0.2182
Geomorphology	0.12	0.11	0.13	0.17	0.18	0.18	0.17	0.16	0.16	1.39	0.1543
Slope	0.09	0.07	0.07	0.09	0.12	0.14	0.14	0.14	0.13	0.98	0.1089
Lineament Density	0.07	0.05	0.04	0.04	0.06	0.09	0.10	0.11	0.11	0.69	0.0764
Soil Depth	0.06	0.04	0.03	0.03	0.03	0.05	0.07	0.08	0.09	0.48	0.0533
Elevation	0.05	0.04	0.03	0.02	0.02	0.02	0.03	0.05	0.07	0.33	0.0370
Ground Water level	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.23	0.0259
Drainage Density	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.17	0.0189
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	09	1.00

Table 7: Consistency Measures

Layer	Geology	LULC	Geomorphology	Slope	Lineament Density	Soil depth	Elevation	Ground Water level	Drainage Density	Total	Consistency Measures	Consistency Measures
Geology	1.00×0.31	2.00×0.22	3.00×0.15	4.00×0.11	5.00×0.08	6.00×0.05	7.00×0.03	8.00×0.03	9.00×0.02	2.9700	2.9700/ 0.3069	9.68
LULC	0.50×0.31	1.00×0.22	2.00×0.15	3.00×0.11	4.00×0.08	5.00×0.05	6.00×0.03	7.00×0.03	8.00×0.02	2.1250	2.1250/ 0.2182	9.74
Geomorphology	0.33×0.31	0.50×0.22	1.00×0.15	2.00×0.11	3.00×0.08	4.00×0.05	5.00×0.03	6.00×0.03	7.00×0.02	1.4923	1.4923/ 0.1543	9.67
Slope	0.25×0.31	0.33×0.22	0.50×0.15	1.00×0.11	2.00×0.08	3.00×0.05	4.00×0.03	5.00×0.03	6.00×0.02	1.0251	1.0251/ 0.1089	9.41
Lineament Density	0.20×0.31	0.25×0.22	0.33×0.15	0.50×0.11	1.00×0.08	2.00×0.05	3.00×0.03	4.00×0.03	5.00×0.02	0.7115	0.7115/ 0.0764	9.31
Soil depth	0.17×0.31	0.20×0.22	0.25×0.15	0.33×0.11	0.50×0.08	1.00×0.05	2.00×0.03	3.00×0.03	4.00×0.02	0.4905	0.4905/ 0.0533	9.20
Elevation	0.14×0.31	0.17×0.22	0.20×0.15	0.25×0.11	0.33×0.08	0.50×0.05	1.00×0.03	2.00×0.03	3.00×0.02	0.3397	0.3397/ 0.0370	9.18
Ground Water level	0.13×0.31	0.14×0.22	0.17×0.15	0.20×0.11	0.25×0.08	0.33×0.05	0.50×0.03	1.00×0.03	2.00×0.02	0.2401	0.2401/ 0.0259	9.27
Drainage Density	0.11×0.31	0.13×0.22	0.14×0.15	0.17×0.11	0.20×0.08	0.25×0.05	0.33×0.03	0.50×0.03	1.00×0.02	0.1758	0.1758/ 0.0189	9.30
											Total	84.76

Table 8: Parameters of AHP to check consistency of the matrix.

AHP parameters	Formula	Values	Remarks
Consistency Measures	$\frac{\text{(Row of comparison Matrix)} \times \text{(Eigen Vector)}}{\text{Corresponding Eigen Vector of the row}}$	Table 7	Last column of the consistency table
Principal Eigen Value	λmax	9.42	Average of the column of Consistency Measures (Table7)
Consistency Index (CI)	$\frac{\lambda max - n}{n - 1}$	0.0525	n is number of thematic layers equal to 9 (n = 9)
Consistency Ratio (CR)	$\frac{CI}{RI}$	0.036	RI is Random Index equal to 1.45 from Table 3 (n=9)

The matrix is considered consistent if all the elements have been obtained from the minimal amount of its elements. Moreover, the elements of the columns and rows of a consistent matrix will be proportional. The consistency measures used for the present study are presented in Table 7. The parameters used to determine the consistency of the normalized matrix via the AHP method are presented in Table 8 and Eq. (1). Consistency ratio (CR) was computed using Eq. (1). CI is the consistency index and the term (n) is a random index that is completely based on the value of n. The values of RI (n) for n≤10 is listed in Table 3. The Consistency Ratio (CR) is calculated to determine how consistent the matrix is, with a CR value of 0.10 or lower being acceptable (Valentinas Podvezko, 2009) [17]. In this study, the Consistency Ratio (CR) for the weights assigned to the different thematic maps is 0.036, as shown in Table 8. This value indicates that the matrix is consistent and the weight assignments are reliable.

Weighted Overlay Analysis

The "Weighted Overlay" tool in ArcGIS's Spatial Analyst Tools was used to perform an overlay analysis, combining multiple raster layers with assigned weights to evaluate groundwater potential. For Weighted Overlay Analysis, these all thematic layers must be in same scale hence a score/weight i.e. 1,3,5,7,9 was assigned to each layer. The high weighted valuve was considered as groundwater prospective areas. The relative importance of different thematic layers and their corresponding classes were used for groundwater potential zone map. The analysis classified the study area into four categories: excellent, good, moderate, and poor groundwater potential, as shown in Figure 14. The results (Table 10) indicate that 26.99 km^2 (1.05%) of the area have excellent groundwater potential, 1287.16 km^2(50.07%) have good potential, 843.71 km^2 (32.82%) have moderate potential, and 412.86 km^2 (16.06%) have poor potential.

Validation of groundwater potential zones

The groundwater potential zones map, was validated by comparing it with groundwater recharge well data for the year 2023. This recharge well data was calculated with the help of pre and post-monsoon groundwater level data provided by the Groundwater Survey and Development Agency (GSDA), Ahmednagar. The validation confirmed the accuracy and reliability of the map in identifying groundwater potential zones. It was observed that the number of wells in the poor, moderate, good and excellent potential zones were 2, 9, 5 and 9 respectively. The Groundwater recharge map of the study area was superimposed on the groundwater potential zones map of study area (Fig 15).

Table 9: Weights for thematic layers using AHP method

Sr. No	Influencing factor	Value	Eigen Value	% Weightage
1	Geology	High	0.31	31
2	LULC	↓	0.22	22
3	Geomorphology		0.15	15
4	Slope		0.11	11
5	Lineament Density		0.08	8
6	Soil depth		0.05	5
7	Elevation		0.03	3
8	Ground water level		0.03	3
9	Drainage Density	Low	0.02	2
Total				100

Groundwater Potential Zones = (Geomorphology) x (15) + (Geology) x (31) + (Slope) x (11) + (land use land cover) x (22) + (Drainage density) x (02) + (Elevation) x (03) + (Lineament Density) x (08) + (Soil) x (05) + (Ground Water Depth) x (03)

Table 10: Area under different ground water potential zones

Sr. No	GW Potential Zones	Area(km^2)	Per cent of total area
1	Poor	412.86	16.06
2	Moderate	843.71	32.82
3	Good	1287.16	50.07
4	Excellent	26.99	1.05
Total		2570.73	100

Table 11: GWPZ and Groundwater recharge depth

GW Potential Zones	Per cent of total area under zones	Groundwater recharge depth (m)	Per cent of area under recharge zones	No. of wells in the zones
Poor	16.06	2.1 – 2.3	17.48	2
Moderate	32.82	2.4 -2.6	37.49	9
Good	50.07	2.7 - 2.9	16.80	5
Excellent	1.05	3.0 – 3.3	28.23	9
Total	100	Total	100	25

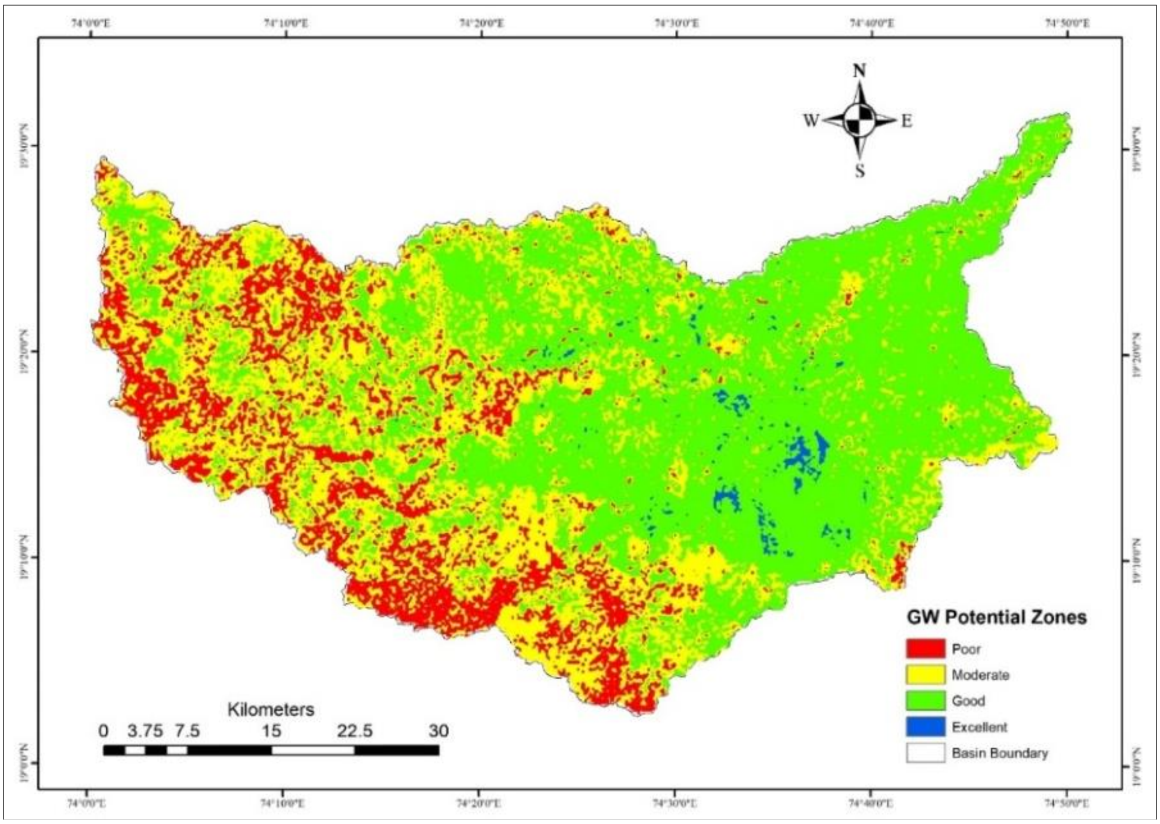

Fig 14: Ground water potential map of Mula River basin of Ahmednagar district

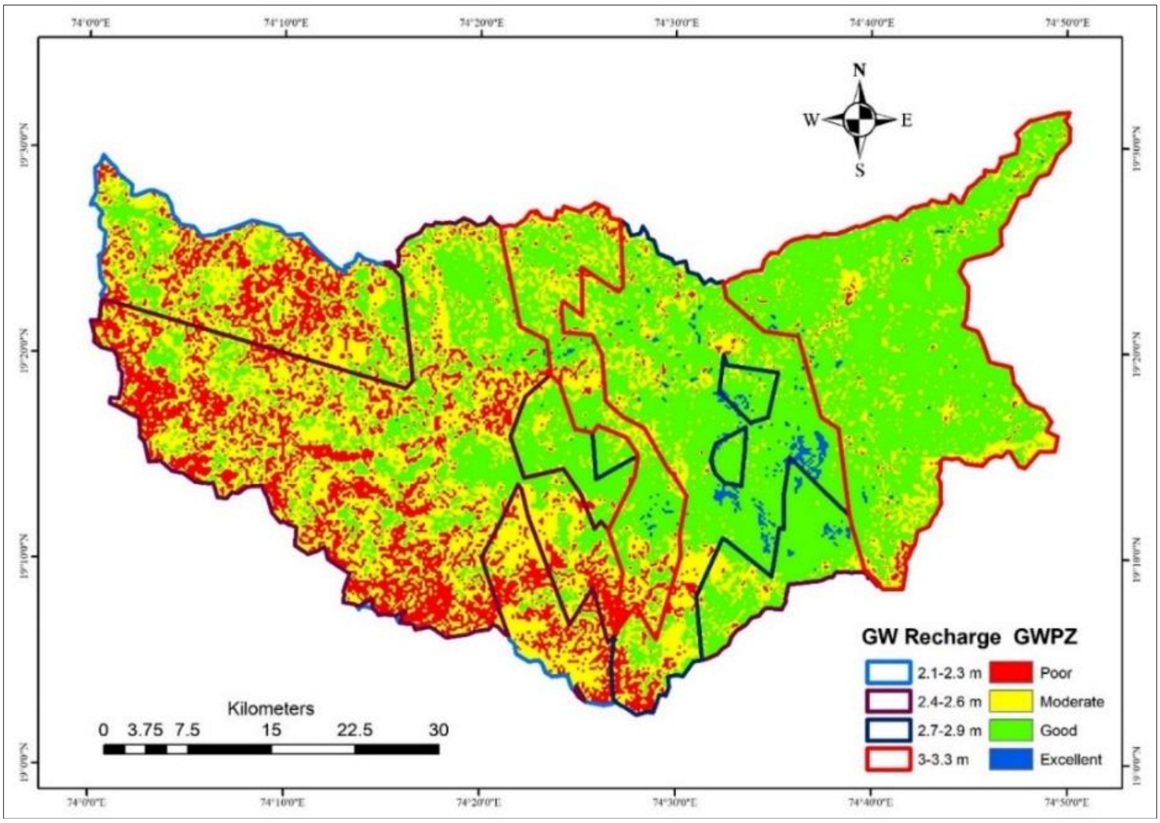

Fig 15: Validation of Mula River basin in Ahmednagar district

Conclusion

The study reveals that integration of nine thematic maps such as drainage density, slope, geology, geomorphology, lineament density, soil depth, elevation, land use/land cover and groundwater level give first-hand information to local authorities and planners about the areas suitable for groundwater exploration. Results show that 26.99 km^2 (1.05%) have excellent groundwater potential, 1287.16 km^2 (50.07%) have good potential, 843.71 km^2 (32.82%) have moderate potential, and 412.86 km^2 (16.06%) have poor groundwater potential. High drainage density (2.20 – 3.40 km/km^2) is found in the North-Eastern and Central East regions of Mula River basin of Ahmednagar district covering 6.17% of total study area. The Elevation of the Mula River basin ranged between 408 m to 1095 m above the mean sea level. Mula River basin has a very gentle slope covering 37.76% of total area and only 0.13% of area has a very steep slope. Mula River basin has majority of the area under the Agricultural land covering 49.97% of total study area followed by the Forest having 41.34% of the total area. Only 0.01% of study area has waste-lands. The geological formation of Mula River basin consists of Deccan Traps. The geomorphological class majorly found in Mula River basin is Pediment Pedi-plain complex covering almost 64.34% of total area, followed with Moderately dissected plateau with 31.86% of total area. Majority of the soil in Mula River basin is Moderately Shallow soil (0.25 – 0.5 m) covering 41.89% of total study area, whereas only 4.55% of total study area is Shallow soil with depth ranging from 0.25 to 0.5 m. The highest lineament density was observed in the south-eastern part of Mula River basin with only 2% of total study area. The groundwater level depth for pre-monsoon ranged between 5.2 to 8.6 m, whereas for post-monsoon the level was 5.8 to 10 m. The study also recommends using GIS technology combined with remote sensing data and the AHP method for further analysis of groundwater potential zones, as this approach can reduce costs, save time, and require less manpower while providing greater accuracy. The maps generated through this method can serve as an initial guide for local authorities and water policymakers in choosing appropriate locations for drilling new open wells. Consequently, identifying areas with developed aquifers can aid in the responsible use and sustainable management of water resources.

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