Delineation of potential groundwater recharge zones for the North Gujarat region of Gujarat state using RS & GIS and MCDA techniques

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ABSTRACT

The rapid increase in population and industrialization has significantly raised the consumption of groundwater resources for domestic, agricultural, and industrial purposes. This study aims to develop groundwater recharge potential zone maps to assist in the construction of artificial recharge structures in the North Gujarat Region of Gujarat, India. An integrated approach combining remote sensing (RS), geographical information system (GIS), and multi-criteria decision analysis (MCDA) was used to achieve this goal. Various factors influencing groundwater availability, including geology, soil, lineament density, slope, rainfall, land use/land cover, geomorphology, and drainage density, were analyzed to delineate potential groundwater recharge zones. The influence of each parameter was determined using Saaty's Analytic Hierarchy Process (AHP) method, and sub-parameters were ranked according to the AHP scale. A weighted overlay analysis tool in ArcGIS software was employed to map the groundwater recharge potential zones in the North Gujarat region. The results classified the area's recharge potential as Excellent (9.93%), Good (27.90%), Moderate (17.58%), Poor (3.92%), and Very Poor (0.92%) of the total area. These findings provide valuable insights for effectively planning and managing groundwater resource development in the region.

Keywords: *Potential groundwater recharge zones, Groundwater recharge, Analytical hierarchy process, Geographical information system, Remote sensing, North Gujarat Region.*

1. INTRODUCTION

Groundwater is one of the most precious and important components in the natural water cycle stored under the water table in pore spaces of soil/rock [1]. Its availability serves as a source of an essential component in domestic, agricultural, and socio-economic development activities [2,3]. The increasing demand for water for the domestic, irrigation and industrial sectors has created increasing pressure on this natural resource which is a point of concern in highly populated and industrialized nations of the world, such as India, China and African countries [4,5]. Urbanization, deforestation, and industrialization have serious implications for groundwater quantity and quality [6-7].

Groundwater extraction for household, agricultural, and industrial purposes is estimated as 36%, 42%, and 27%, respectively, worldwide Groundwater provides 80–90% of the Indian rural population's domestic water supply [8] and 50% of water demand by the urban population and industrial sector depends on groundwater. In highly populated countries like India, groundwater used for irrigation is over 50% of the agricultural land [9]. The use of groundwater resources in India is very extensive and uncontrolled. As a result of scarce availability, many parts of India face high water stresses and continuous extraction has resulted in aquifer stress and deterioration in quality. A similar scenario can be seen in other highly populated countries [10,11].

Groundwater quality in Gujarat state is highly variable and due to a multiplicity of factors *viz*. influenced by direct sea water encroachment, inherent sediment salinity, water logging, overexploitation leading to overall deterioration in groundwater quality, coupled with domestic and industrial pollution etc. The groundwater scenario in the state is not very encouraging due to an imbalance between recharge and groundwater exploitation. Further, the water demand has increased manifold owing to agricultural, industrial and domestic requirements and this has led to water scarcity in many parts of the state, which is likely to become more severe in the coming future due to both natural and manmade factors. Therefore, sustainable development of groundwater resources requires a precise quantitative assessment based on reasonably valid scientific principles. Hence, the delineation of groundwater potential zones (GWPZ), has acquired great significance [12].

Artificial groundwater recharge is pivotal, particularly considering that over 45% of the nation's irrigation relies on groundwater.2 With growing demands from agriculture, households, and industries, the daily draft on groundwater continues to rise. Therefore, in the present study, we explored the integration of remote sensing (RS) and Geographic Information Systems (GIS) to create a composite picture of the North Gujarat Zone characteristics, analyse rainfall-runoff potential, and identify potential groundwater recharge zones.

2. METHODOLOGY

2.1 Study area overview

Gujarat is located on the west coast of India surrounded by the Arabian Sea in the West, Rajasthan in the North and North-East. The total area of Gujarat state is 196 lakh ha.

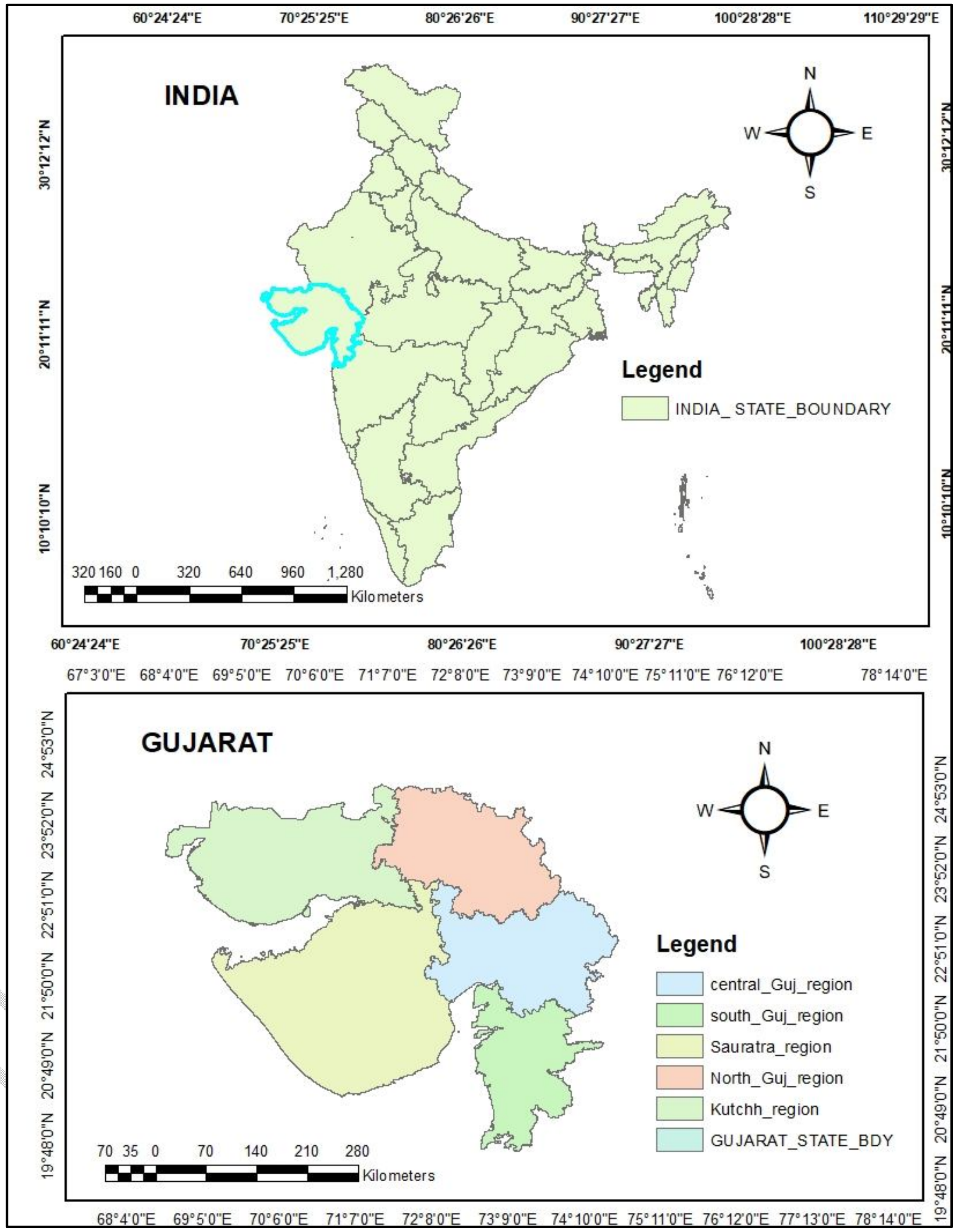

Fig. 1. Study area map of North Gujarat Zone generated by ArcGIS 10.4.1

The state has 3 distinct geographical regions, a corridor which is the agricultural and industrial mainland (South Gujarat, Central Gujarat and North Gujarat), a peninsula known as Saurashtra, and Kutch, which is partly desert and partly marshland. Gujarat is covered by several large and small river basins, which are characterized by varied and complex hydrogeological, agroclimatic and hydrological features. The North region Of Gujarat State is lies between 21˚25'N and 22˚10'N latitudes and 70˚45'E and 71˚20'E longitudes. The North Gujarat region has a total geographical area of 32.37 lakh ha which includes a total 6 districts like Aravalli (3.22 lakh ha), Banskantha (12.70 lakh ha), Gandhinagar (2.16 lakh ha), Mehsana (4.39 lakh ha), Patan (5.73 lakh ha) and Sabarkantha (4.17 lakh ha).

2.2 Data acquisition

Precipitation data spanning the years 1981 to 2020 were collected from various stations, with the data obtained through the State Data Centre in Gandhinagar and the Gujarat State Disaster Management Authority. Slope and drainage density thematic layers were created using open-source digital elevation data from the SRTM DEM, which was sourced from the Earth Explorer-USGS database. Geological and geomorphological maps were retrieved from the Bhukosh Geological Survey of India database. Additionally, the soil map, developed by the National Bureau of Soil Survey & Land Use Planning (NBSS&LUP), was provided by BISAG in Gandhinagar. (Table 1).

Table 1. Different input parameters are used to analyze the potential groundwater zones for the north Gujarat region.

Data	Description	Source
Rainfall data	Annual average rainfall	Gujarat State Disaster Management Authority. (http://www.gsdma.org/). State Water Data Centre, Gandhinagar.
Remote Sensing Data	LULC SRTM DEM	Bhaskaracharya Institute for Space Application and Geo-informatics (BISAG), Gandhinagar. EarthExplorer-USGS (https://earthexplorer.usgs.gov/)
Conventional data	Soil map	Bhaskaracharya Institute for Space Application and Geo-informatics (BISAG), Gandhinagar.
	Geomorphology Geology	Bhukosh – Geological Survey of India. (http://bhukosh.gsi.gov.in/Bhukosh/Public)
	Lineament	Bhuvan Indian Geo platform of ISRO https://bhuvan.nrsc.gov.in/home/index.php

2.3 Demarcation of potential groundwater recharge zones

The various thematic maps were processed to delineate the potential groundwater zones.

2.3.1 Base Map

The base map is the foundational representation, delineating the boundary of the North Gujarat Region watershed – the primary region of interest. It functions as the fundamental reference map for all subsequent thematic maps. The base map was created with 30 m spatial resolution using SRTM DEM data. The mosaic tool was used to merge them. The Fill and Sink tools were used to remove defects in the DEM. Flow Direction, Flow Accumulation, and streams were generated.

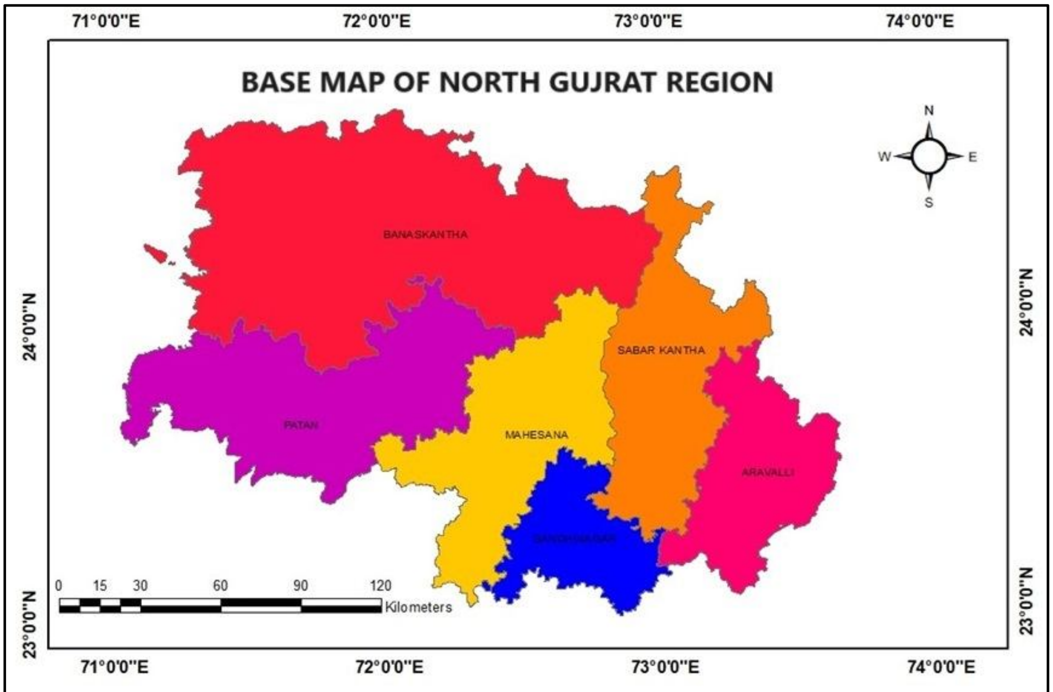

Fig. 2. Base map of North Gujarat region generated through ArcGIS 10.4.1

2.3.2 Geomorphology

Geomorphology, which illustrates various landforms and topographic features, plays a significant role in identifying zones with groundwater potential. It highlights the distribution of different landform processes and influences such as temperature changes, geochemical interactions, water flow, and freeze-thaw cycles [13,14]. In this study, geomorphological data for Gujarat State, India, were acquired from the Bhukosh-Geological Survey of India's open-source resources. Using ArcGIS 10.4.1, a raster file of the Geomorphology Map for the North Gujarat Region was developed. To enhance compatibility and clarity for further analysis, the data underwent reclassification using the "classify tool" within the spatial analyst function of ArcGIS 10.4.1.

2.3.3 Rainfall

Rainfall is the key driver of the hydrological cycle and a major factor affecting groundwater recharge. Infiltration varies with rainfall intensity and duration; high-intensity, short-duration rainfall leads to more runoff and less infiltration, while low-intensity, long-duration rainfall allows for greater infiltration. In this study, daily rainfall data from 1981-2020 were used to calculate average precipitation. The annual weighted rainfall for the area was determined using the Thiessen polygon method, dividing the region into 27 polygons, each linked to a specific station. A rainfall map for North Gujarat was created using the Inverse Distance Weighted (IDW) Interpolation method, where weights decrease as the distance from sampling points increases[14].

2.3.4 Slope

Slope is a crucial terrain feature that indicates the steepness of the land surface and provides insight into the geologic and geodynamic processes at a regional level. The slope significantly affects surface runoff and infiltration rates, with steeper slopes reducing groundwater recharge. On steep slopes, rainwater flows rapidly, limiting the time available for infiltration into the saturated zone, whereas gentler slopes allow for greater infiltration[14]. In this study, DEM data was employed to generate a slope map, and the slope tool in ArcGIS was used to create a raster file, representing the slope in percentages.

2.3.5 Drainage Density

The drainage density is inversely proportional to permeability or infiltration [14]. Drainage density is determined by dividing the total length of all rivers within a drainage basin by the total area of that specific basin [15].

2.3.6 Soil

Soil is a vital natural resource that plays a crucial role in identifying potential groundwater zones and is essential for agricultural productivity. It significantly influences groundwater recharge, as soil characteristics directly affect the movement of surface water into subsurface systems. These characteristics are closely linked to the rates of infiltration, percolation, and permeability, which in turn impact the soil's ability to retain and absorb water[15].

2.3.7 Lineament Density

Lineaments are direct features observed on Earth’s surface, indicating zones of structural movement or weakness in the Earth's crust. Lineament density was calculated using the mathematical formula [16].

2.3.8 Geology

The geological composition plays a significant role in determining the occurrence and groundwater flow within a particular area. The rock types in a specific area significantly influence the accessibility and replenishment of groundwater reserves. In this study, the resource map was scanned, rectified, and georeferenced using the Arc GIS 10.4.1 software, and the map of Geology for the North Gujarat Region River Basin was constructed[15].

2.3.9 Land Use Land Cover (LULC)

Land use involves various human activities and intentions on a specific land. In contrast, land cover encompasses vegetation, water bodies, rocks/soil, artificial structures, and other features arising from land modifications [14].

2.4 Saaty’s Analytical Hierarchy Process

In the Analytical Hierarchy Process (AHP), decision-makers assign individual weights to evaluation criteria through pairwise comparisons., indicating their relative importance. Subsequently, for a specific criterion, each option is given ratings based on the decision maker's comparisons in a pairwise manner. The AHP consolidates these weights assigned to criteria and the scores allocated to options to calculate an overall score for each option, establishing a ranking. The global score is calculated as a weighted sum across all criteria. Notably, 9 signifies higher importance, 1/9 denotes the least, and 1 signifies equal weight for a parameter or category. Using these weighted criteria, each parameter in the study was categorized accordingly [17] (**Table 3**).

2.5 Integration of various thematic maps to Delineate the potential groundwater recharge zones (PGWRZ)

Several thematic maps, representing various groups and their standardized weights, were integrated within the ArcGIS 10.4.1 platform. The Potential Groundwater Recharge Zone Index (PGWRZI) was calculated by combining all thematic layers in the GIS environment using the equation specified by [18]

$$\text{GWRPZI} = \sum_{i}^{n}(X_A \times Y_B)$$

Where,

PGWZI = Potential Groundwater Zones Index,

X_A- Denotes the weightage of the thematic layers, where A = 1, 2, 3, …….., X

Y_B- Signifies the rank of the thematic layers’ subclass, where B = 1, 2, 3, ….., Y

3. RESULTS AND DISCUSSION

3.1 Study area: The North region Of Gujarat State is lies between 21˚25’N and 22˚10’N latitudes and 70˚45’E and 71˚20’E longitudes. The North Gujarat region has a total geographical area of 32.37 lakh ha which includes a total 6 districts like Aravalli (3.22 lakh ha), Banaskantha (12.70 lakh ha), Gandhinagar (2.16 lakh ha), Mehsana (4.39 lakh ha), Patan (5.73 lakh ha) and Sabarkantha (4.17 lakh ha).

The AHP pair-wise matrix was created by assigning scale weights to themes and features, considering their impact on groundwater occurrence. This involved synthesizing insights from literature reviews and expert opinions. A pair-wise comparison matrix, established in an 8 x 8 format using Saaty's analytical hierarchy process, determined influenced weights for each theme based on a rating scale. The consistency ratio of the assigned weights falls within the predefined range of (0.084 < 0.10); it can be concluded that the matrix is consistent, and the allocated weights are deemed acceptable (Table 2).

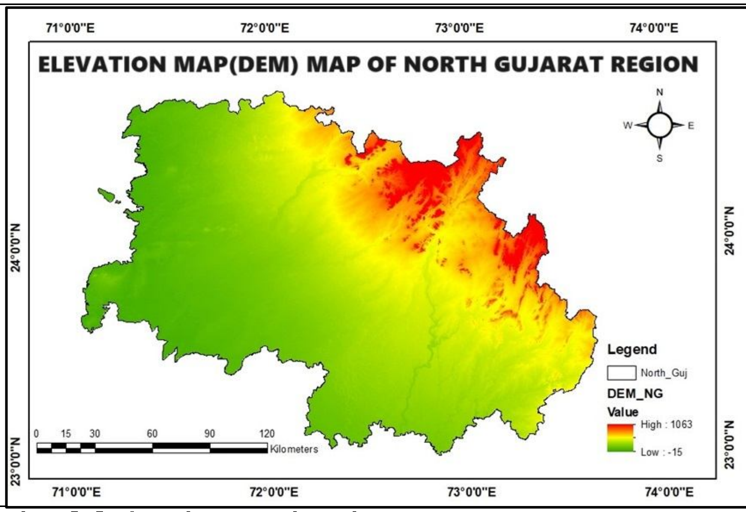

Fig.3 [A] Elevation map (DEM)

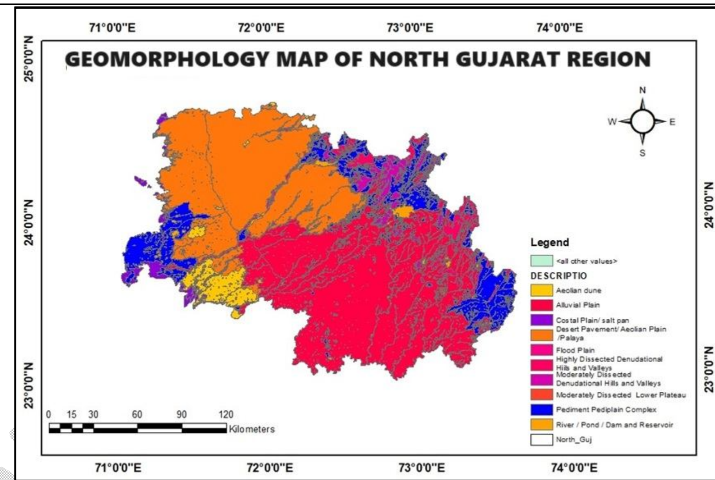

Fig. 3[B] Geomorphology map

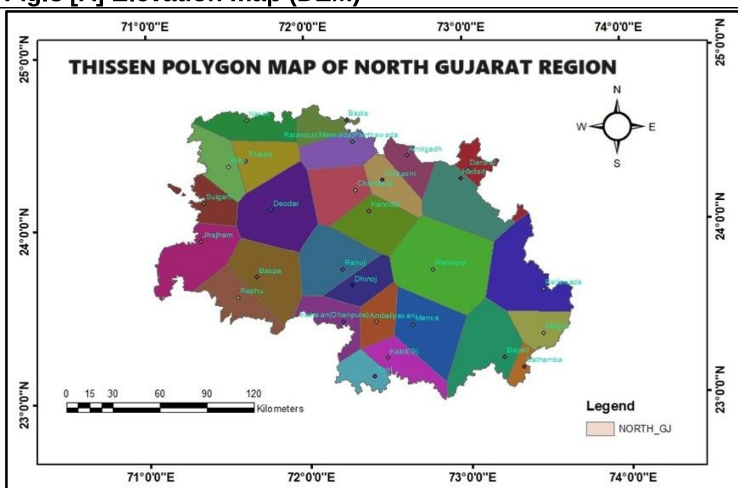

Fig. 3[C] Thiessen Polygon map for rain gauge stations

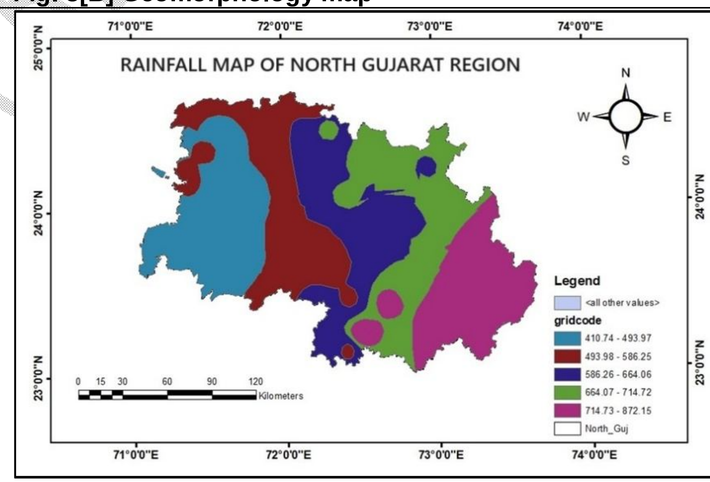

Fig. 3[D] Rainfall map

Fig.3. [A] Elevation map, [B] geomorphology map, [C] Thiessen polygon map, and [D] Rainfall map of North Gujarat Zone generated using ArcGIS 10.4.1

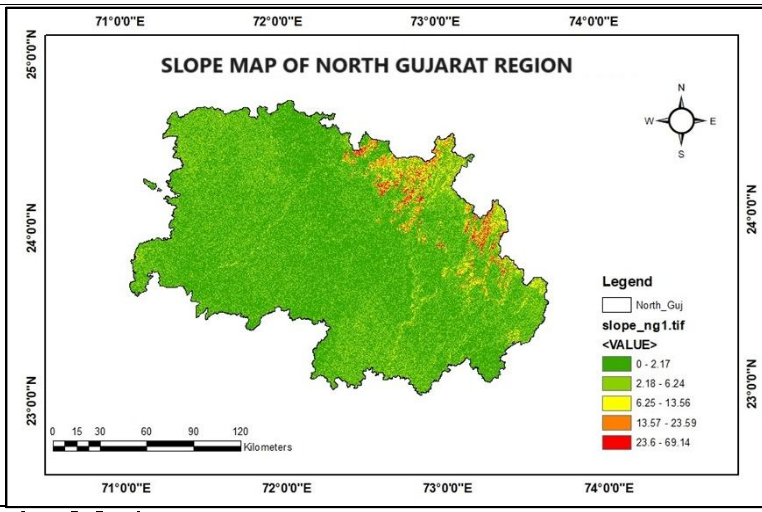

Fig. 4[A]. Slope map

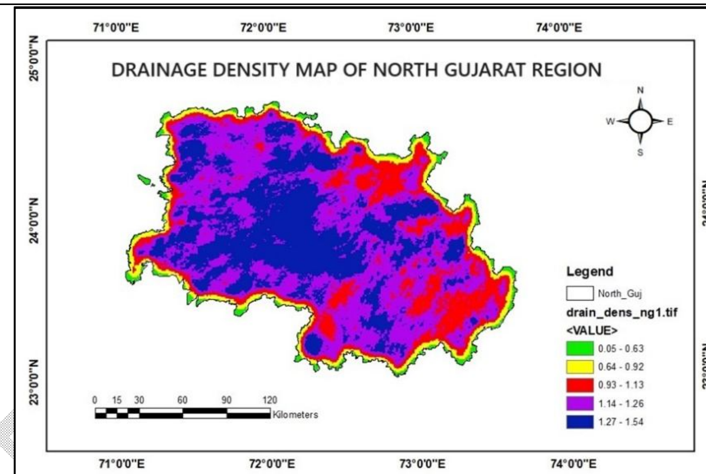

Fig. 4[B]. Drainage Density map

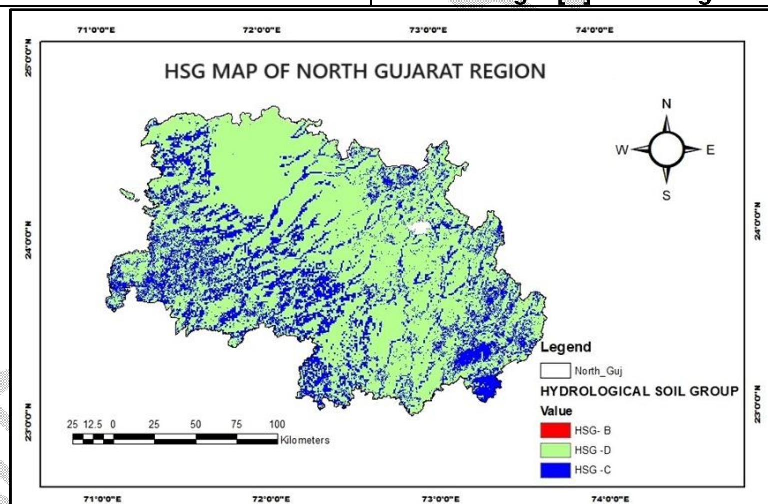

Fig. 4[C]. Soil map (HSG)

Fig. 4 : [A] Slope map, [B] Drainage map, [C] Drainage density map Soil map of the North Gujarat Region generated through ArcGIS 10.4.1.

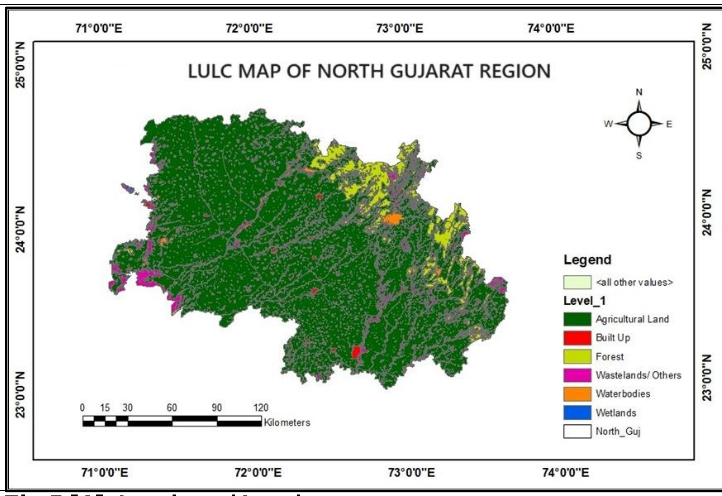

Fig.5 [A]. Land use/ Land cover map

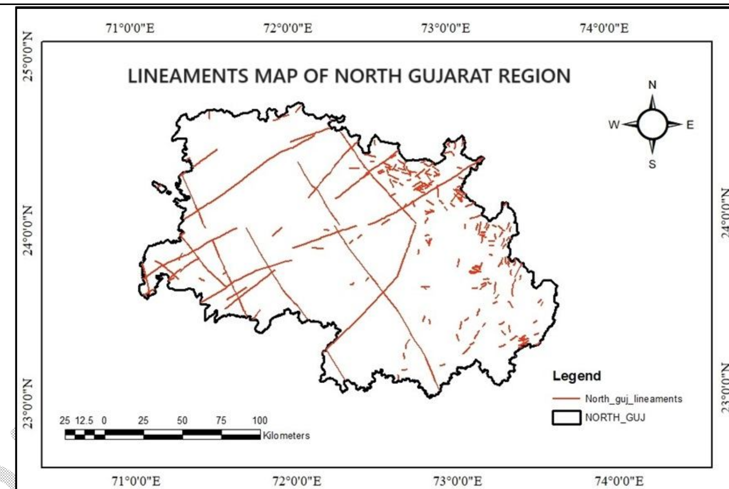

Fig.5 [B]. Lineament map

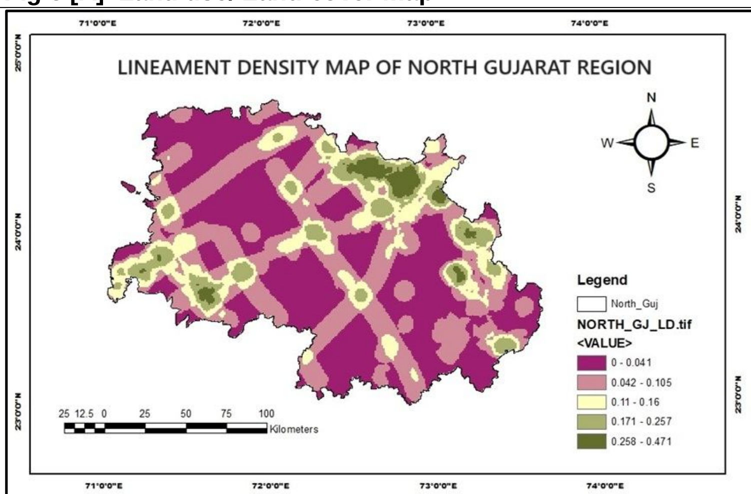

Fig.5 [C]. Lineament Density map

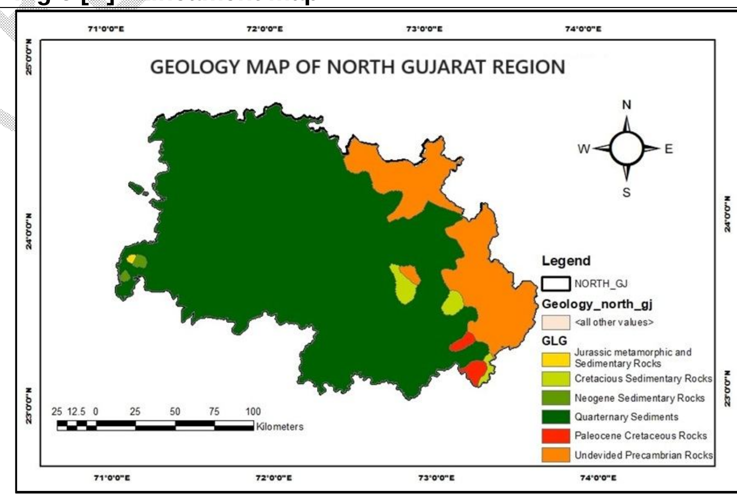

Fig.5 [D]. Geology Map

Fig. 5. [A] Land cover map, [B] Lineament map, [C] Lineament density map, and [D] Geology map of the North Gujarat region generated through ArcGIS 10.4.1.

Table 2. A pair-wise matrix calculation determines the weight assigned to the thematic layers.

Layers	SL	GEO M	SO	GEO	LULC	DD	R	LD
GEO M	3	1	6	7	5	5	3	4
R	5	0.33	6	9	7	5	1	8
SL	1	0.33	3	7	5	2	0.20	6
DD	0.50	0.20	2	6	3	1	0.20	5
SO	0.33	0.16	1	5	2	0.5	0.16	3
LULC	0.20	0.20	0.5	3	1	0.33	0.14	2
LD	0.16	0.25	0.33	3	0.5	0.2	0.11	1
GEO	0.14	0.14	0.20	1	0.33	0.16	0.11	0.33
TOTAL	**10.34**	**2.62**	**19.03**	**41**	**23.83**	**14.20**	**4.93**	**29.33**

Where, SL = Slope; GEOM = Geomorphology; SO = Soil; GEO= Geology; LU-LC = Land use / land cover; DD = Drainage Density; R = Rainfall; LD = Lineament Density

The smaller the consistency index, the higher the consistency of the matrix. In the ideal case, CI = 0. The ideally consistent matrix is a rare case, even if the 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 (Table 3).

Table 3. Parameters of AHP to check the consistency of weights assigned to thematic layers.

Parameter	Formula	Value
Consistency measures	$\frac{\text{(A column of comparison Matrix) x (Eigen Vector)}}{\text{Corresponding Eigen Vector of the row}}$	70.66
Principal Eigen Value	$\lambda_{max} = \frac{70.63}{8} = 8.83$	8.83
Consistency Index (CI)	$\frac{\lambda_{max} - n}{n-1} = \frac{8.83-8}{8-1} = 0.119$	0.119
Consistency Ratio (CR)	$\frac{\text{CI}}{\text{RCI}} = \frac{0.119}{1.41} = 0.084$	0.084

The normalized matrix is derived from a pair-wise comparison matrix by adding the entries in each column of the comparison matrix and dividing each entry a_{jk} by the sum of the entries in the corresponding column $\sum a_{jk}$ of the comparison matrix. The sum of normalized entries in each column will equal one (Table 4).

Table 4: Normalized Weights for thematic layer

Sr. No.	Parameters	Value	Eigen Value	Normalized Weightage %
1	**Geomorphology**	**High**	**0.307**	**31**
2	**Rainfall**		**0.283**	**28**
3	**Slope**		**0.143**	**14**
4	**Drainage density**		**0.097**	**10**

5	**Soil**		**0.065**	**7**
6	**Land use/landcover**		**0.044**	**4**
7	**Lineament Density**		**0.036**	**4**
8	**Geology**	**Low**	**0.020**	**2**
		Total		**100**

Table 5. Weightage allocation to various subclasses of the thematic layers

Parameter	Parameter weight (%)	Sub-class	Potential Groundwater Recharge	Saaty's scale	Relative weight
Drainage Density (km/km^2)	**10**	0 - 2.17	Very high	9	36
		2.18 - 6.24	High	7	28
		6.25 - 13.56	Moderate	5	20
		13.57 - 23.59	Low	3	12
		23.6 - 69.14	Very low	1	4
			Total	**25**	**100**
Geomorphology	**31**	River / Pond / Dam and Reservoir	Very high	9	21
		Pediment pediplain complex	High	7	17
		Flood plain	High	7	17
		Alluvial plain	High	7	17
		Moderatelydissected structural lower plateau	Moderate	5	7
		Moderately dissected denudational hills and valleys	Low	3	7
		Desert pavement/ aeolian plain /palaya	Low	3	7
		Highly dissected denudational hiils and valleys	Very low	1	2
		Costal plain/ salt pan	Very low	1	2
		Aeolian dune	Very low	1	2
			Total	**43**	**100**
Geology	**2**	Quarternary sediments	Very high	9	28
		Paleocene cretaceous rocks	Very high	9	28

		Undevided precambrian rocks	Moderate	5	16
		Cretaceous sedimentary rocks	Moderate	5	16
		Neogene sedimentary rocks	Low	3	9
		Jurassic metamorphic and Sedimentary rocks	Very Low	1	3
			Total	**32**	**100**
Lineament Density (km/km^2)	**3.6**	0.258 - 0.471	Very High	9	36
		0.171 - 0.257	High	7	28
		0.106 - 0.17	Moderate	5	20
		0.042 - 0.105	Low	3	12
		0 - 0.041	Very Low	1	4
			Total	25	100
Slope (%)	**14**	0 - 2.17	Very High	9	36
		2.18 - 6.24	High	7	28
		6.25 - 13.56	Moderate	5	20
		13.57 - 23.59	Low	3	12
		23.6 - 69.14	Very Low	1	4
			Total	25	100
Landuse / land cover	**4**	Wetlands	Very High	9	27
		Waterbodies	High	9	27
		Agricultural Land	Moderate	7	20
		forest	low	5	15
		Wastelands/Others	low	3	9
		Build up	Very low	1	2
			Total	34	**100**
Soil (According to HSG	**7**	B	Very High	9	50
		C	High	7	39
		D	Very low	2	11
			Total	**18**	**100**

The Elevation map DEM prepared for the North Gujarat Region (Fig. 3[A]) shows the highest elevation of 1063 m and the lowest Elevation of -15 m. The alluvial pain covers the highest vast area of 12.65 lakh ha, constituting 41.53 % of the total region, while the coastal plain covers 0.51 lakh ha, 1.68% of the basin area (Fig. 3[B]) and (Table 5). The average precipitation using the Thiessen Polygon Method, the IDW interpolation technique was used to develop the rainfall map of the North Region of the basin. The highest rainfall in the region was recorded to be 872.15 mm, whereas the lowest rainfall was recorded as 410.74 m. (Fig. 3[C-D]). In the analysis of slope percentages, the range of 0-2 % encompasses the highest area, covering 18.19 lakh ha, which accounts for a substantial 59.74 % of the total area, while the range of 23.6 - 69.14% represents the lowest area, with only 0.25 lakh ha (Fig. 4[A]) and (Table 5). The drainage density, range of (1.14 - 1.26) km/km^2 represents the highest area, covering 12.11 km^2, which accounts for a significant 39.79% of the total area, while the range of (0.05 - 0.63) km/km^2 signifies the lowest area, with just 1.08 km^2 (3.54 %) of the total area (Fig. 4[C] and (Table 5).

Group D has the highest area among the hydrologic soil groups, covering 22.48 lakh ha, representing 73 % of the total area. In contrast, Group B, with an area of 0.23 lakh ha, constitutes a smaller portion, accounting for 0.74 % of the total area (Fig. 4[D]) and (Table 5). In the Land Use Land Cover (LULC) categories, agricultural land is the most extensive, covering 24.83 lakh ha, constituting 81.55% of the total area. Conversely, forest, with an area of only 2.04 lakh ha, represents the smallest category, making up just 6.70 % of the total area (Fig. 5[A]) and (Table 5). The lineament density km/km^2 covers a substantial area of 11.33 lakh ha, accounting for 37.20 % of the total. In contrast, the 0.258 - 0.471 km/km^2 range represents a much smaller area, comprising only 1.39 lakh ha or 4.56% of the total area (Fig. 5[B-C]) and (Table 5). In geology features, Quarternary sediment rocks dominate with the highest area covering 24.82 lakh ha, representing 81.51 % of the total area. On the other hand, Paleocene cretaceous rocks cover the least area, measuring 0.3 lakh ha, representing 0.87 % of the entire area (Fig. 5[D]) and (Table 5).

3.3 DEMARCATION OF POTENTIAL GROUNDWATER RECHARGE ZONES

After assigning various weights to the thematic layers and their respective attributes, the next step was to integrate these thematic maps within the ArcGIS platform. This integration was performed using the "weighted overlay" tool in the spatial analyst module. The Potential Groundwater Recharge Zone Index (PGRZI) was utilized to identify and classify areas with groundwater recharge potential. The results of the overlay analysis were categorized into five zones based on their recharge suitability: Very Poor, Poor, Moderate, Good, and Excellent zone (Fig. [7]). The analysis highlights the potential groundwater recharge zones in the North Gujarat region. Upon interpretation, it was found that over half of the study area falls under the combined categories of good and moderate recharge potential, indicating favorable conditions for groundwater replenishment. Specifically, areas with excellent recharge potential account for 0.94 lakh hectares (3.08%), while zones with good potential span 9.96 lakh hectares (32.73%). The majority of the region, covering 15.31 lakh hectares (50.27%), is classified as having moderate recharge potential. In contrast, the zones with poor and very poor recharge potential collectively cover approximately 4.24 lakh hectares (13.92%). The spatial distribution of these recharge zones is detailed in (Table 6).

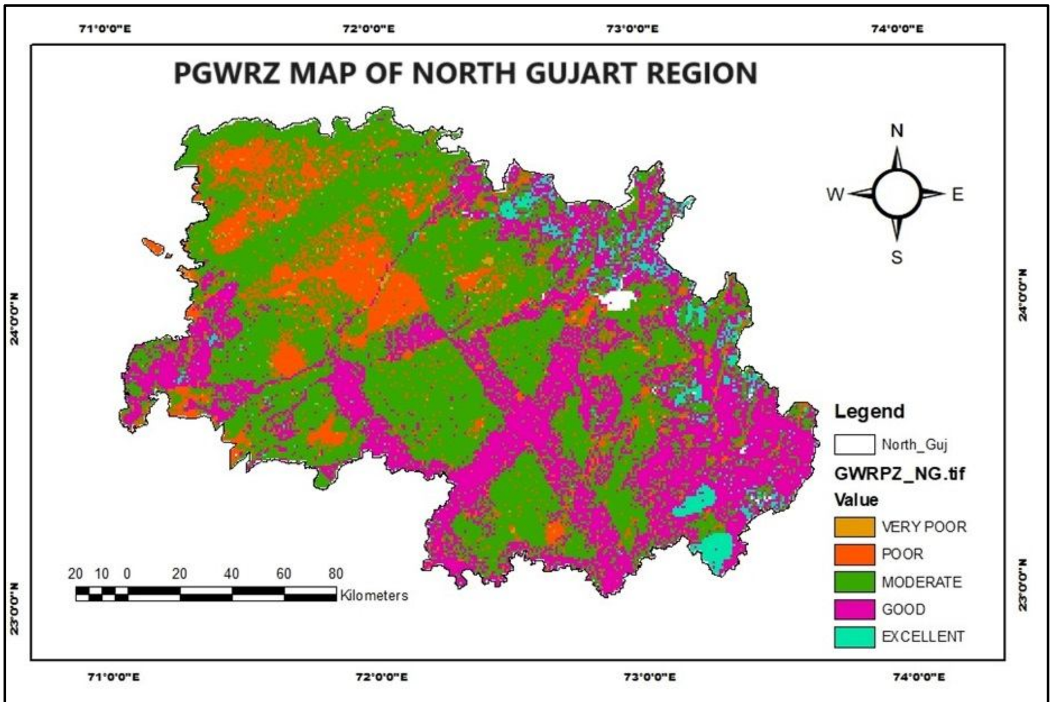

Fig 6. Potential groundwater recharge zones of the North Gujarat Region generated through ArcGIS 10.4.1

Table 6: Potential groundwater recharge zones of the North Gujarat Region

Sr. No.	PGWRZ	Area, lakh ha	Area (%)
1	Excellent	0.94	3.08
2	Good	9.96	32.73
3	Moderate	15.31	50.27
4	Poor	4.04	13.27
5	Very poor	0.20	0.65

In the present investigation, we demarcate the potential groundwater recharge zones using remote sensing and GIS. Many researchers used the integration of MCDA, AHP, RS, and GIS to Identify potential groundwater recharge zones and storage structures [20, 15, 21,15]. A similar study was conducted by of the Mand catchment of the Mahanadi River basin using RS and GIS and suggested groundwater potential zones with very low, low to medium, medium to high, and very high groundwater potential encompassing an area of 962.44 km^2, 2019.92 km^2, 969.19 km^2, and 1380.42 km^2, respectively. The present investigation showed five distinct zones based on groundwater recharge potential. 'Excellent' (50.50 km^2, 2.36 %), 'Good' (1376.78 km^2, 64.56 %), 'Moderate' (599.14 km^2, 28.09 %), 'Poor' (90.67 km^2, 4.25 %), and 'Very Poor' (15.32 km^2, 0.718 %). A similar study using RS, GIS, and MCDA showed four groundwater potential zones such as very- high (523.58 km^2), high (798.22 km^2), moderate (646.04 km^2), and low (456.66 km^2) were suggested. Based on these, suitable storage structures and area distributions such as check dams, percolation ponds, flood and furrows, and ditch and furrows were suggested [22].

Future studies should focus on the various hydrological models to forecast future surface-water abstraction scenarios within a complex river basin amidst climate change. Development of GIS-based hydrological models based on precipitation, evapotranspiration, land use, soil properties, and topography and groundwater level data of available and future climate data of the semi-arid and arid zones may help in suggesting a suitable location-specific climate-resilient cropping system based on the crop's water requirement and water availability in the groundwater for the next 30 years to ensure the livelihood security of farmers.

4. CONCLUSION

Combining Remote Sensing and GIS technologies has demonstrated a rapid and cost-efficient approach to groundwater prospecting and exploration. A significant portion of the area is favorable to groundwater recharge. It was found that over half of the study area falls under the combined categories of good and moderate recharge potential, indicating favorable conditions for groundwater replenishment. Specifically, areas with excellent recharge potential account for 0.94 lakh hectares (3.08%), while zones with good potential span 9.96 lakh hectares (32.73%). Most of the region, covering 15.31 lakh hectares (50.27%), is classified as having moderate recharge potential. In contrast, the zones with poor and very poor recharge potential collectively cover approximately 4.24 lakh hectares (13.92%). The spatial distribution of these recharge zones is detailed in (Table 7).

REFERENCES

1. Fitts, C. R. (2002). Groundwater Science. Academic Press.

2.Ayazi, M. H., Pirasteh, S., Arvin, A. K. P., Pradhan, B., Nikouravan, B. and Mansor, S. (2010). Disasters and risk reduction in groundwater: Zagros Mountain Southwest Iran using geoinformatics techniques. Disaster Advances, 3: 51–57.

3. Pradhan, B. (2009). Groundwater potential zonation for basaltic watersheds using satellite remote sensing data and GIS techniques. *Open Geoscience*, 1: 120–129.
4. Das, S. (2017). Delineation of groundwater potential zone in hard rock terrain in Gangajalghati block, Bankura district, India using remote sensing and GIS techniques. *Modeling Earth Systems and Environment*, 3**(4):** 1589-1599.

5. Manap, M. A., Sulaiman, W. N. A., Ramli, M. F., Pradhan, B. and Surip, N. (2011). A knowledge-driven GIS modeling technique for groundwater potential mapping at the Upper Langat basin, Malaysia. *Arabian Journal of Geosciences*, **6:** 1621-1637.

6. Todd, D. K. and Mays, L. W. (2004). Groundwater hydrology. John Wiley and Sons.

7. Singh, S. K., Zeddies, M., Shankar, U. and Griffiths, G. A., (2019). Potential groundwater recharge zones within New Zealand. Geoscience Frontiers, 10:1065–1072.

8. Agarwal, R. and Garg, P. K. (2016). Remote sensing and GIS based groundwater potential & recharge zones mapping using multi-criteria decision-making technique. *Water Resources Management*, 30**(1):** 243–260.

9.Anonymous (2014). National Water Development Agency Report. (https://www.nwda.gov.in/upload/uploadfiles/files/ar2014-15.pdf), accessed at 20th August, 2023.

10. Anonymous (2018). NITI Aayog – annual report 2017–2018. (https://www.niti.gov.in/annual-reports), accessed at 23th August, 2023.

11. Anonymous (2011). World Bank, India groundwater governance. Washington: World Bank. (http://www.worldbank.org/water). accessed at 20th August, 2023.

12. Dabral, S., Bhatt, B., Joshi, J. P. and Sharma, N. (2014): Groundwater suitability recharge zones modelling – A GIS application, *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, **8**: 347–353.

13. Chowdhury, A., Jha, M. K. and Chowdary, V. M. (2010). Delineation of groundwater recharge zones and identification of artificial recharge sites in West Medinipur district, West Bengal, using RS, GIS, and MCDM techniques. *Environmental Earth Sciences*, 59**(6):** 1209-1222.
14.Arulbalaji, P., Padmalal, D., & Sreelash, K. (2019). GIS and AHP Techniques Based Delineation of Groundwater Potential Zones: a case study from Southern Western Ghats, India. Scientific Reports, 9(1), 2082. https://doi.org/10.1038/s41598-019-38567-x
15. Horton, R. Drainage Basin Characteristics. American Geophysical Union Trans. 1932; 13: 350–361.
16.Greenbaum, D. (1985). Review of remote sensing applications to groundwater exploration in basement and regolith. British Geological Survey Report, OD-85, (8): 36.
17. Saaty, T. L. (1980). The analytic hierarchy process mcgraw hill, new york. Agricultural Economics Review, 70(804), 10-21236.
18. Achu, A. L., Thomas, J., & Reghunath, R. (2020). Multi-criteria decision analysis for delineation of groundwater potential zones in a tropical river basin using remote sensing, GIS and analytical hierarchy process (AHP). Groundwater for Sustainable Development, 10, 100365. https://doi.org/10.1016/j.gsd.2020.100365.

19. Bera, A., Mukhopadhyay, B. P., & Barua, S. (2020). Delineation of groundwater potential zones in Karha river basin, Maharashtra, India, using AHP and geospatial techniques. Arabian Journal of Geosciences, 13(15), 693. https://doi.org/10.1007/s12517-020-05702-2
20. Anand, B., Karunanidhi, D., & Subramani, T. (2021). Promoting artificial recharge to enhance groundwater potential in the lower Bhavani River basin of South India using geospatial techniques. Environmental Science and Pollution Research, 28(15), 18437–18456. https://doi.org/10.1007/s11356-020-09019-1.
21. Farhat, B., Souissi, D., Mahfoudhi, R. et al. GIS-based multi-criteria decision-making techniques and analytical hierarchical process for delineation of groundwater potential. Environ Monit Assess 195, 285 (2023). https://doi.org/10.1007/s10661-022-10845-8
22. Akhtar, S., & Rampurawala, A. (2024). Integrating Remote Sensing Data and MODFLOW Modeling for Sustainable Groundwater Resource Management and Monitoring in the Guinea Region, West Africa. Journal of Geography, Environment and Earth Science International, 28(1), 50-64.