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Delineation of Groundwater Potential Zones Using GIS and Analytic Hierarchy Process in Parts of Varanasi and Chandauli Districts

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ABSTRACT

This study employs Remote Sensing (RS) and Geographic Information Systems (GIS) to delineate groundwater potential zones. Various thematic layers, including geomorphology, land use and land cover, geology, rainfall, slope, soil composition, drainage density, and the Topographic Wetness Index (TWI), were integrated using a weighted linear combination in the GIS platform's spatial analyst tool. The Analytic Hierarchy Process (AHP) was used to assign different ranks to these layers and their sublayers. Groundwater potential zones were categorized as poor (16.54%, 96.25 km²), moderate (67.20%, 391.13 km²), and good (16.26%, 94.62 km²). Validation involved observing water levels in various wells within the study area, with the results' reliability assessed using a Receiver Operating Characteristic (ROC) curve, demonstrating an accuracy of 88%. The study area faces rapid urbanization and industrialization, stressing the aquifer's groundwater availability. Identifying groundwater potential zones is thus crucial for effective groundwater development and management.

INTRODUCTION

Groundwater, serving as a fundamental water resource for potable consumption and agricultural irrigation in numerous regions within the country, is crucial for environmental sustainability and serves as a vital freshwater source for human civilization (Arkoprovo et al. 2012, Gleeson et al. 2012, Zhu & Abdelkareem, 2021). Rapid urbanization and industrialization have increased the water demand, leading to a decline in groundwater levels in certain regions, and thus, identifying potential groundwater zones is an optimal solution (Ajay Kumar et al. 2020, Melese & Belay 2021, Saravanan et al. 2021, Tamiru & Wagari 2021, Zhu & Abdelkareem 2021). Remote sensing (RS) data has been identified as a cost-effective alternative to conventional approaches, such as hydrogeological surveys (Chowdhury et al. 2009, Jha et al. 2010, Kumari & Singh 2021). Over the past few decades, the application of geospatial methods has risen as a pivotal tool in groundwater mapping (Murthy 2000). Assessing groundwater potential requires a thorough review of all factors impacting its movement, whether directly or indirectly (Gaur et al. 2011, Sternberg & Paillou 2015, Nanda et al. 2017). The integration of various satellite data sources has facilitated the comprehensive and efficient analysis of different groundwater potential zones (Shekhar & Pandey 2014). Several research studies have highlighted that identifying areas with groundwater potential is shaped by a variety of landscape, climatic, and environmental factors. These factors comprise land use and land cover (LULC), geology, geomorphology, rainfall, slope, drainage density, soil, lineament structure, topography, and river distance, among others (Jaiswal et al. 2003, Gou et al. 2015, Thapa et al. 2017, Parameswari & Padmini 2018, Das & Pal 2020, Pande et al. 2020, Doke et al. 2021). The hydrological and groundwater dynamics within a specific geographical area are determined by the underlying principles of geomorphology and geology (Shaban et al. 2006, Doke et al. 2018, Doke et al. 2021). Water percolation rates depend upon an area's geological attributes, particularly its lithological composition, thereby impacting the mechanism of groundwater replenishment (Dar et al. 2020). Groundwater replenishment relies significantly on drainage systems and analyzing basin structures to estimate recharge zones. Low drainage density areas often see higher groundwater

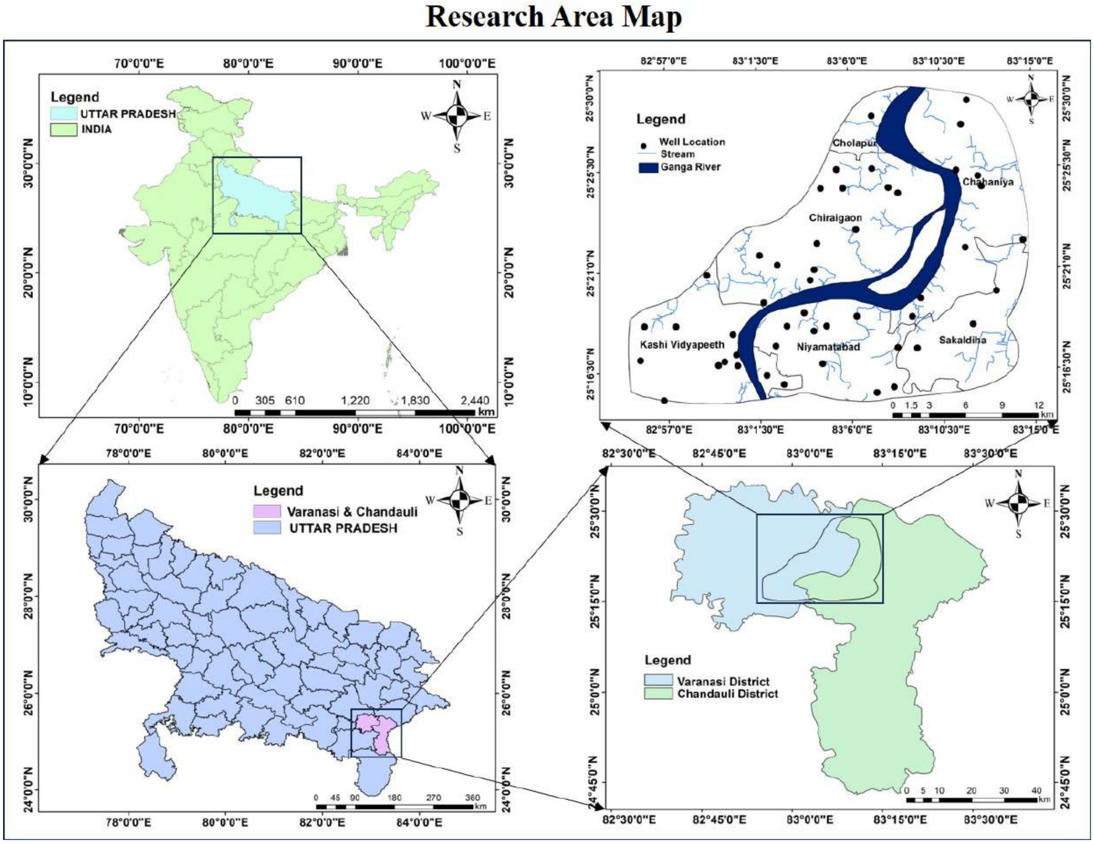

Fig. 1: Map of the research area.

recharge. Topography, like steep slopes, hampers rainwater infiltration, reducing recharge. Land use changes affect water retention, impacting evapotranspiration, runoff, and recharge. Understanding this link is crucial due to landscapes' vulnerability to human activities. Efficient land use greatly influences groundwater recharge and demand dynamics (Lerner & Harris 2009, Fan 2015). The Topographic Wetness Index focuses on the moisture levels and soil attributes within a particular area (Beven & Kirkby 1979, Radula et al. 2018). In the research area, rapid development and urbanization result in limited availability of land for groundwater recharge and over-extraction of groundwater. The research focuses on identifying groundwater potential areas in parts of Varanasi and Chandauli districts in Uttar Pradesh, utilizing Geographic Information System (GIS) and Analytical Hierarchy Process (AHP) techniques. The goal of this study is to enhance the management and planning of groundwater resources.

RESEARCH AREA

The research area is situated within the Survey of India toposheets numbered 63 O/3 and 63 K/15, spanning from latitude 25°15'0" N to 25°29'0" N and longitude 82°55'0" E to 83°15'0" E in the eastern region of Uttar Pradesh, India as shown in Fig. 1. The research area is situated in part of the Indo-Gangetic plain, encompassing an area of 582 square kilometers that is predominantly characterized by alluvial plains. The research area experiences a tropical climate, significantly influenced by the monsoon. About 80% of the annual precipitation in the region is 1,020 mm and occurs during the southwest monsoon. The research area is located at an average elevation of 76 meters above mean sea level (MSL). Geologically, the area is primarily characterized by Pleistocene to recent Quaternary alluvial sediments (Raju et al. 2011). The occurrence of regular flood events leads to the sedimentation of fresh silt, clay, and loam in the more recent alluvial deposits found near drainage channels. These deposits contribute to the formation of an aquifer system distinguished by alternate sand and clay layers (Nandimandalam 2012). The research area comprises shallow as well as deeper aquifers. The shallow aquifer is situated close to the surface and is distinguished by the presence of sandy sediments. It occurs at the water table condition and is unconfined. In contrast to the alluvial aquifer near the surface, the deeper aquifers in the research area exhibit semi-confined to confined conditions. These aquifers are situated at greater depths and are typically composed of various geological formations with lower permeability than shallow aquifers (Central Ground Water Board 2021). The decline in groundwater levels in the research area is attributed to extensive groundwater pumping, a consequence of population growth and urbanization.

MATERIAL AND METHODS

Data Source and Process of Preparing Thematic Layers

Numerous elements, such as land use and land cover (LULC), geology, geomorphology, rainfall, soil composition, slope, drainage density, and topographic wetness index (TWI) are used to categorize diverse groundwater potential zones (Yeh et al. 2016, Maity & Mandal 2019, Doke et al. 2021). The thematic maps of LULC, geomorphology, geology, rainfall,

Table 1: Data source and processing used for preparation of different thematic layers.

Thematic Layers	Data Source	Processing
LULC	Bhuvan	The imagery downloaded from Bhuvan and the research area has been extracted.
Geomorphology	Bhukosh	The shapefile was downloaded from Bhukosh and extracted the geomorphology map of the research area.
Geology	USGS	Downloaded world geological map and intersected the geology of the research area using GIS.
Rainfall (mm/yr.)	Indian Meteorological Department (IMD), Pune	Interpolation of Rainfall values from rain gauge points using the IDW method
Slope	SRTM- Digital Elevation Model (DEM) 30 × 30 M resolution	DEM is used to extract slope (in degrees)
Soil	FAO Soil portal	Downloaded digital soil map of world shapefile and exported data of research area using GIS.
Drainage Density	SRTM- Digital Elevation Model (DEM) 30 × 30 M resolution	Created in GIS using the Line Density from Spatial Analyst
TWI	SRTM- Digital Elevation Model (DEM) 30 × 30 M resolution	Created using hydrology from the Spatial Analyst tool in GIS.

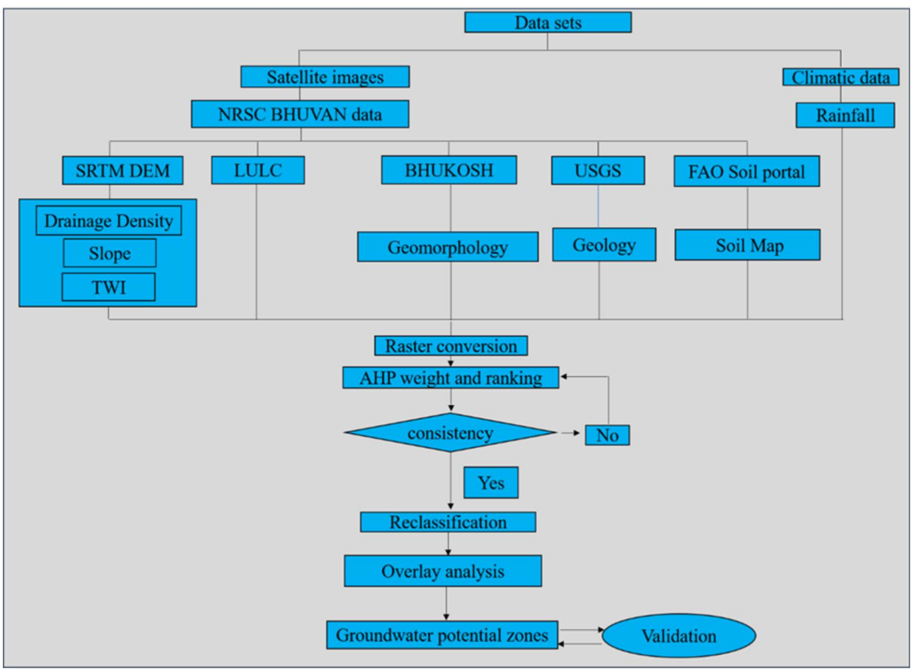

Fig. 2: The flowchart methodology of the research area.

Table 2: Pairwise comparison matrix of eight layers chosen for the present study.

Layer	LULC	GM	GG	RF	SLOPE	SOIL	DD	TWI
LULC	1	2	3	4	5	5	6	7
GM	0.5	1	2	3	4	4	5	6
GG	0.33	0.5	1	2	3	3	4	5
RF	0.25	0.33	0.5	1	2	2	3	4
SLOPE	0.2	0.25	0.33	0.5	1	1	2	3
SOIL	0.2	0.25	0.33	0.5	1	1	2	3
DD	0.167	0.2	0.25	0.33	0.5	0.5	1	2
TWI	0.14	0.167	0.2	0.25	0.33	0.33	0.5	1

LULC landuse/landcover, GM geomorphology, GG geology, RF rainfall, DD drainage density, TWI topographic wetness index.

soil, slope, drainage density, and topographic wetness index (TWI) were prepared using GSI. Table 1 provides a complete overview of the thematic layers, including their data sources and processing methods, while Fig. 2 illustrates the step-by-step methodology in the form of a flowchart.

Assigning Weights and Normalizing through the Analytical Hierarchy Process

Analytical Hierarchy Process (AHP) systematically integrates various criteria and expert opinions into groundwater potential mapping, refining map accuracy and boosting decision-making transparency and reliability (Machiwal et al. 2011, Saravanan et al. 2021). In 1980, Thomas L. Saaty introduced the Analytic Hierarchy Process (AHP), which has become a prominent GIS-based technique extensively used in demarcating zones of groundwater potential (Arulbalaji et al. 2019). AHP employs a pairwise comparison matrix (PCM) to determine the weight of individual layers in the decision-making process which is given in Table 2. Saaty's scale of relative importance and influence is utilized to assign a numerical rank ranging from 1 to 9 to each criterion. Table 3 represents the scales for pair comparison with AHP. Weightage has been assigned to various layers following their significance in identifying the potential groundwater zone (Bera et al. 2020). As a result, the matrix is normalized by calculating the weight of different layers based on subjective evaluation. A normalized pairwise comparison matrix is generated by dividing each value in the matrix by the sum of its respective columns (Bordoloi et al. 2023). To get the criteria weight, the mean of each row is calculated. The sum of criteria weights is one, so it is normalized. The weight assigned to each layer in NPCM is between 0 and 1, as shown in Table 4.

Table 3: Description of scales for pair comparison with AHP (source: Saaty 1980, 1990).

Strength of importance	Explanation
1	Equal importance
3	Medium importance
5	Strong importance
7	Very strong importance
9	Maximum importance
2,4,6,8	Interim number between two adjacent number

The Calculation of Consistency Ratio

The Consistency Index is calculated by using the formula

Table 4: Normalized pairwise comparison matrix and criteria weights.

Layer	LULC	GM	GG	RF	SLOPE	SOIL	DD	TWI	CW
LULC	0.36	0.4	0.4	0.34	0.3	0.3	0.25	0.22	0.325
GM	0.18	0.2	0.26	0.26	0.24	0.24	0.21	0.19	0.225
GG	0.12	0.11	0.13	0.17	0.18	0.18	0.17	0.16	0.153
RF	0.09	0.07	0.066	0.086	0.12	0.12	0.13	0.13	0.10
SLOPE	0.07	0.05	0.044	0.043	0.06	0.06	0.085	0.097	0.064
SOIL	0.07	0.05	0.044	0.043	0.06	0.06	0.085	0.097	0.064
DD	0.06	0.04	0.033	0.029	0.03	0.03	0.042	0.064	0.041
TWI	0.05	0.03	0.026	0.021	0.02	0.02	0.021	0.032	0.028

LULC landuse/landcover, GM geomorphology, GG geology, RF rainfall, DD drainage density, TWI topographic wetness index.

given in Equation 1.

$$\text{Consistency index (CI)} = \frac{(\lambda\_max-1)}{(n-1)} \quad \ldots(1)$$

Where, λ_{max} = Principal Eigenvalue; it is the average of the weighted sum value as calculated in Table 5.

n= number of layers selected for study

The consistency ratio is determined by the ratio between the consistency index (CI) and the random consistency index (RCI), computed using Equation 2.

$$\text{Consistency ratio (CR)} = \frac{CI}{RCI} \quad \ldots(2)$$

Eight thematic layers were chosen for the study, and according to Saaty (1980; 1990), the random consistency index (RCI) value is 1.41 which is given in Table 5. A consistency ratio (CR) equal to or less than 0.10 allows analysis to proceed; however, exceeding this value prompts a review for inconsistencies. In this research, the calculated consistency ratio (CR) falls below the threshold, indicating the analysis can proceed without issues which is calculated in Table 6.

The Calculation of Groundwater Potential Zones

Thematic layers are combined in the weighted overlay analysis method in GIS software using Equation 3.

$$GWPZ= \sum_{i}^{n}(W_{th} \times W_{sb}). \quad \ldots(3)$$

Where GWPZ is Groundwater Potential Zone, W_{th} is Weight assigned to different layers, and W_{sb} is Weight assigned to sub-layers. Sub-layers have been given different rankings, ranging from 1 to 5, depending upon water holding capacity. Sub-layers responsible for good groundwater potential have been assigned 5 rank, and layers responsible for poor groundwater potential have been assigned 1 rank as represented in Table 7.

RESULTS AND DISCUSSION

Land Use Land Cover (LULC)

In the research area, distinct zone has different and specialized land use and land cover which is represented by Fig. 3. The ability of groundwater percolation can be affected by the properties of various types of land cover. Built-up areas, comprising urban and residential developments, commonly exhibit substantial impervious surfaces, such as roads, buildings, and pavements, covering an area of 256.27 km^2. These surfaces impede the infiltration of water into the subsurface, resulting in a decrease in the percolation of groundwater. Nevertheless, precipitation runoff tends to rapidly flow into nearby aquatic systems, resulting in a reduction in the recharge of groundwater. Agricultural lands, comprising an area of 270.37 km^2, frequently exhibit enhanced soil permeability and porosity due to the presence of crops and vegetation cover. The presence of vegetation cover decelerates the velocity of water, facilitating its percolation into the subsurface. Barren land, comprising an area of 29.08 km^2, typically exhibits a scarcity of vegetation cover and a paucity of organic material within the soil. This condition is commonly observed in rocky terrain or regions characterized by sparse vegetation. Consequently, the soil exhibits a deficiency in both structural integrity and organic matter, thereby impeding the facilitation of water infiltration. Barren land typically exhibits a reduced capacity for groundwater percolation. Water bodies, such as rivers, lakes, ponds, and reservoirs, have the potential to enhance

Table 5: The consistency indices of randomly generated reciprocal matrices (source: Saaty 1980, 1990).

Matrix size	1	2	3	4	5	6	7	8
RCI Value	0.00	0.00	0.58	0.90	1,12	1.24	1.13	1.41

Table 6: Calculation of Consistency.

Layer	LULC	GM	GG	RF	SLOPE	SOIL	DD	TWI	Weighted Sum
LULC	0.32	0.45	0.46	0.4	0.32	0.32	0.25	0.2	2.72
GM	0.16	0.22	0.3	0.3	0.26	0.26	0.2	0.17	1.88
GG	0.11	0.11	0.15	0.2	0.19	0.19	0.16	0.14	1.26
RF	0.08	0.075	0.07	0.1	0.13	0.13	0.12	0.11	0.826
SLOPE	0.06	0.056	0.05	0.05	0.06	0.06	0.08	0.08	0.52
SOIL	0.06	0.056	0.05	0.05	0.06	0.06	0.08	0.08	0.52
DD	0.05	0.045	0.04	0.03	0.03	0.03	0.04	0.057	0.33
TWI	0.046	0.037	0.03	0.025	0.02	0.02	0.02	0.028	0.23

Principal Eigenvalues (λ_{max}) =8.2076, n=8, CI=0.0296, RI=1.41, CR=0.0210

Table 7: Different ranks assigned to different subcategories.

Factor	Sub-layers	1	2	3	4	5	CR	Weight
LULC	Water Bodies	1	2	4	5		0.049364	0.483352
	Agricultural Land	0.5	1	3	4			0.302338
	Barren Land	0.25	0.5	1	2			0.136463
	Builtup Area	0.2	0.25	0.5	1			0.077847
Geomorphology	Water Bodies	1	2	4	5		0.049364	0.483352
	Active Flood Plain	0.5	1	3	4			0.302338
	Older flood plain	0.25	0.5	1	2			0.136463
	Older Alluvial Plain	0.2	0.25	0.5	1			0.077847
Geology	Alluvium	1					0	1
Rainfall	1,110-1,044	1	2	3	4	5	0.015763	0.416463
	1,110-957	0.5	1	2	3	4		0.261921
	957-854	0.33	0.5	1	2	3		0.160835
	854-762	0.25	0.33	0.5	1	2		0.098462
	762-681	0.2	0.25	0.33	0.5	1		0.062319
Slope (in degree)	0-1	1	2	3	4	5	0.015763	0.416463
	1-2	0.5	1	2	3	4		0.261921
	2-3	0.33	0.5	1	2	3		0.160835
	3-7	0.25	0.33	0.5	1	2		0.098462
	7-23	0.2	0.25	0.33	0.5	1		0.062319
Soil	Orthic Luvisols	1					0	1
Drainage Density	0-2	1	2	3	4	5	0.015763	0.416463
	2-6	0.5	1	2	3	4		0.261921
	6-11	0.33	0.5	1	2	3		0.160835
	11-16	0.25	0.33	0.5	1	2		0.098462
	16-25	0.2	0.25	0.33	0.5	1		0.062319
TWI	15.44-23.49	1	2	3	4	5	0.015763	0.416463
	12.66-15.44	0.5	1	2	3	4		0.261921
	10.32-12.66	0.33	0.5	1	2	3		0.160835
	7.99-10.32	0.25	0.33	0.5	1	2		0.098462
	4.31-7.99	0.2	0.25	0.33	0.5	1		0.062319

the process of groundwater percolation and recharge the underlying aquifer, covering an area of 26.28 km^2.

Geomorphology

The Research area exhibits distinct features, including an active floodplain, an older floodplain, and an older alluvial plain. The geomorphological map of the research area is shown in Fig. 4 which represents the essential features, for delineating groundwater potential areas. The Research area with a water body has been assigned the highest ranking. An active floodplain is an area situated adjacent to the Ganga River that experiences recurrent inundation events as a consequence of periodic flood events. An active floodplain has been given a higher ranking than an older floodplain. The older floodplain is distinguished by a different river or stream course or a landscape configuration that differs from its current state. Finally, the older alluvial plain is given the lowest ranking as it is formed by the deposition of sediments over a long period through different rivers coming from the highlands.

Geology

The entire research area is mainly alluvium of quaternary age as shown in Fig. 5. The lithological composition of the

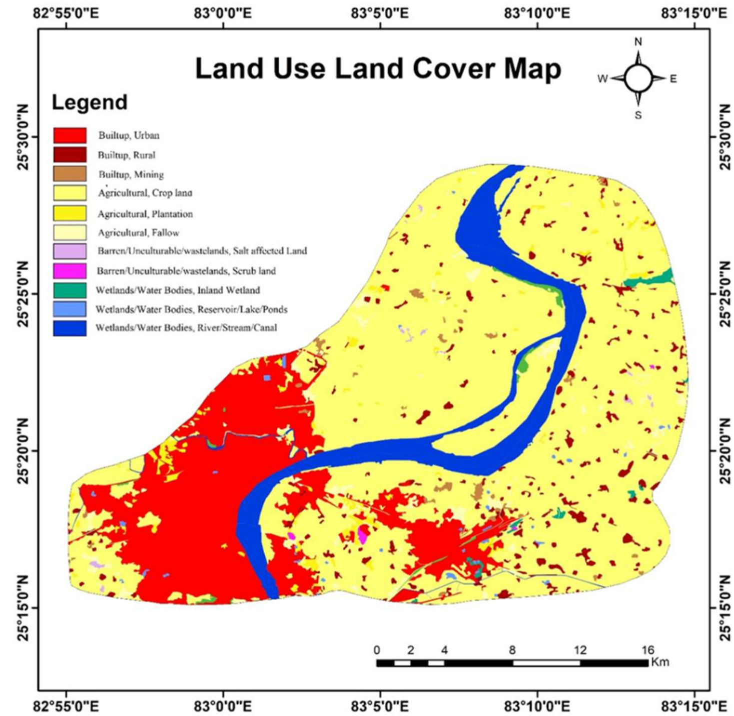

Fig. 3: Land use and land cover map of research area.

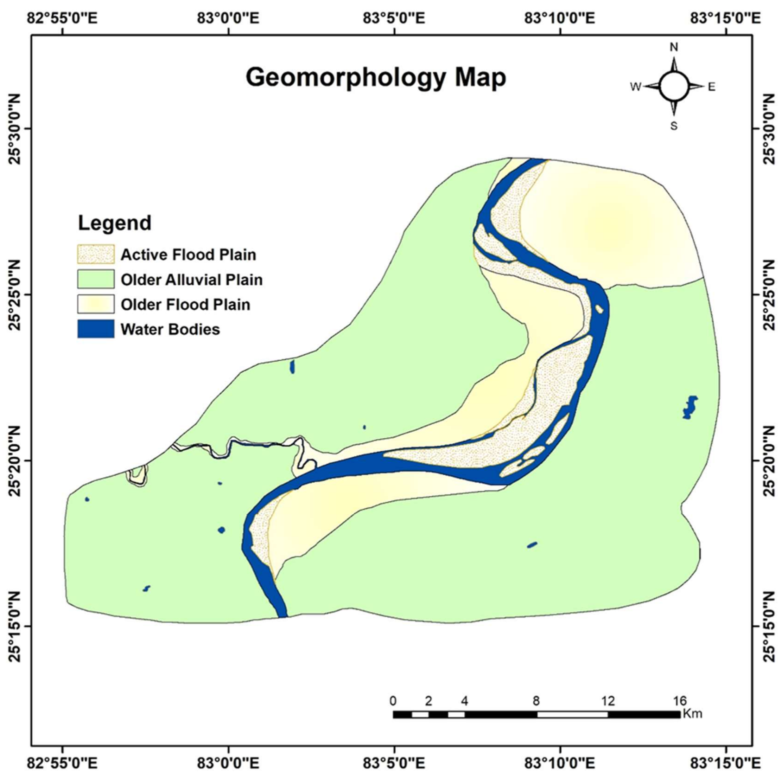

Fig. 4: Geomorphology map of research area.

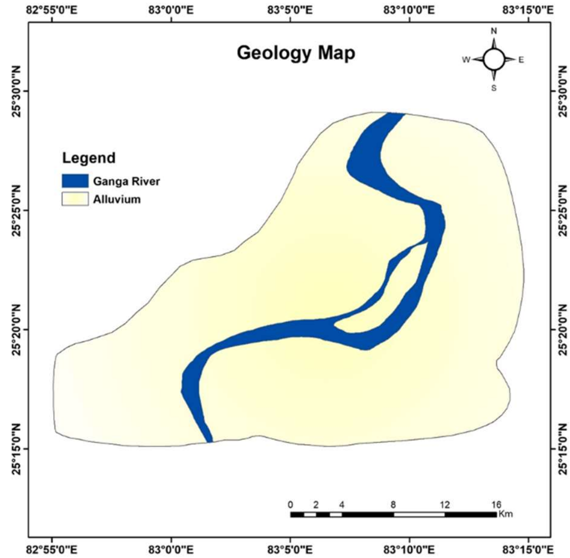

Fig. 5: Geology map of research area.

strata of a region has crucial significance in the assessment of its groundwater potential (Moges et al. 2019). The storage, movement, and availability of groundwater are influenced by the composition and characteristics of the sediments or rocks found in the subsurface. The research area encompasses alluvial sediments that are anticipated to consist of various components, including sands, silts, clays, and gravel. In general, these sediments exhibit good levels of porosity and permeability when compared to lithified rock formations. The sediments in the research area exhibit good permeability, facilitating the movement of water through them and consequently enhancing their capacity to retain groundwater.

Rainfall

The research area has a tropical climate, and the monsoons have a strong effect on it. The southwest monsoon brings about 80% of the area's total annual rainfall of 1,020 mm during June and August. 10-year rainfall data has been taken from IMD, for creating a rainfall distribution map in the

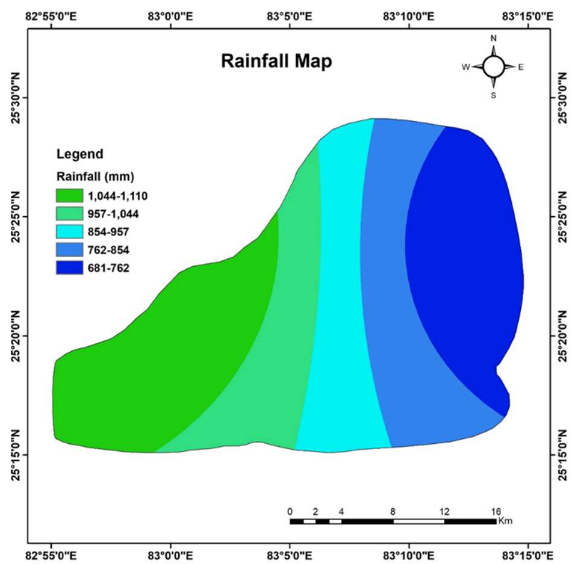

Fig. 6: Rainfall map of research area.

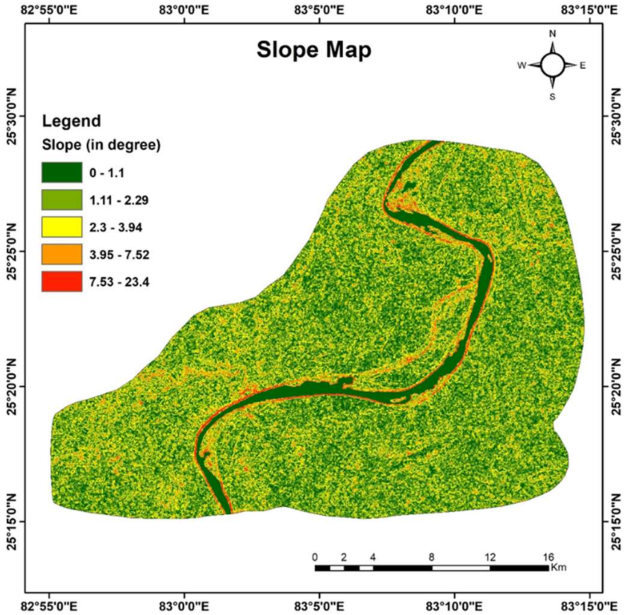

Fig. 7: Slope map of the research area.

research area. The average annual rainfall in the research area is classified into five categories: very low (681-762), low (762-854), moderate (854-957), high (957-1044), and very high (1044-1110), as shown by Fig. 6. The eastern region of the research area exhibits a high intensity of rainfall, which gradually decreases towards the western direction of the research area. The research area with high rainfall has good groundwater potential. As a result, areas with high-intensity rainfall have been assigned a high rank, while areas with low-intensity rainfall have been assigned a low rank.

Slope

The slope is an important feature in the determination of the groundwater potential zone. The gradient of a terrain relates to the change in elevation, and it governs the impact of gravitational force on the flow of water (Kom et al. 2022). It affects the amount of water infiltration. A lower value denotes a gentle slope, while a higher value signifies a steeper slope. In areas with gentle slopes, groundwater recharge takes longer due to ample time for rainwater to seep down. Conversely, steep slopes facilitate rapid rainwater flow, minimizing percolation time. Thus, gentle slopes receive higher rankings while steep ones are ranked lower due to these differences in recharge dynamics. The slope map of the research area is represented in Fig. 7.

Soil

Soil characteristics contribute to shaping the assessment of groundwater potential. The relationship between the porosity and permeability of soil is directly correlated to the rates of infiltration and surface runoff (Senapati & Das 2022). The predominant soil type identified in the research area is orthic luvisols. Fig. 8 shows the soil map of the research area. The diverse mineral composition and elevated nutrient levels found in these soils render them highly suitable for a broad spectrum of agricultural activities. The Luvisols are characterized by a loamy texture, consisting of a substantial amount of silt and an average clay content ranging from 30 to 45 percent (Walmsley et al. 2020). The uniformity of the soil in the research area suggests a consistent influence on its surroundings.

Drainage Density

Drainage density, the mean length of stream channels per unit area, is a measure of how frequently streams occur on the land surface (Avtar et al. 2011).

$$\text{Drainage density} = L/A \quad \ldots(4)$$

Where, L= length of stream channels

A = Area

The assessment of drainage density in a given region is crucial for comprehending its hydrological attributes, including phenomena such as surface runoff, infiltration, and groundwater recharge. Additionally, it has the potential to offer valuable insights into the fundamental lithological composition and geomorphological mechanisms that contribute to the formation and evolution of the landscape (Murmu et al. 2019).

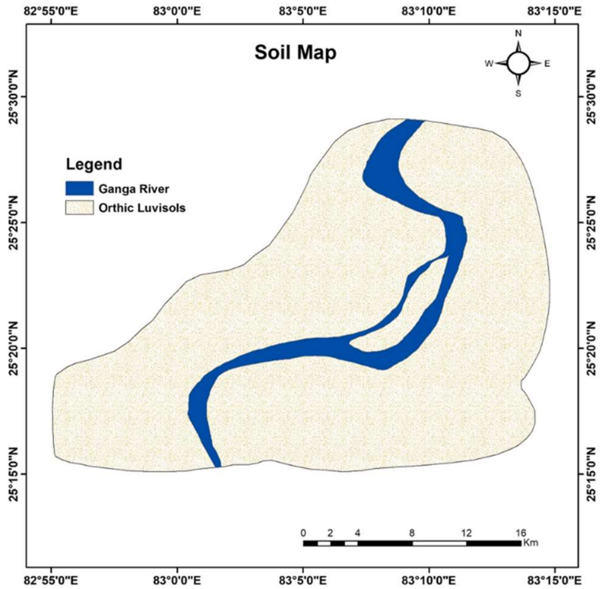

Fig. 8: Soil map of the research area.

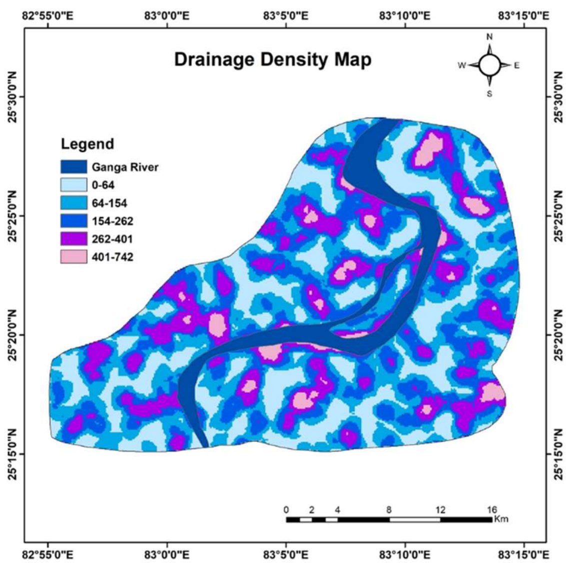

Fig. 9: Drainage density map of research area.

The rate at which groundwater is recharged depends upon the drainage density of the research area. Regions characterized by lower drainage density typically exhibit greater potential for groundwater resources as a result of increased groundwater replenishment. Areas with high drainage density typically exhibit a reduced ability for groundwater recharge as a result of the high rate of surface runoff (Ghosh et al. 2023, Prasad et al. 2008). Therefore, lower drainage density areas have been assigned a high value, and high drainage density areas have been assigned a lower value. The drainage density of the research area is categorized into five distinct categories, namely 0-64, 64-154, 154-262, 262-401, and 401-742 as represented by Fig. 9. A higher numerical value is indicative of a region with a higher drainage density, while a lower numerical value suggests a region with a lower drainage density.

Topographic Wetness Index

It refers to the spatial distribution of water in the soil that is influenced by the topographical features of

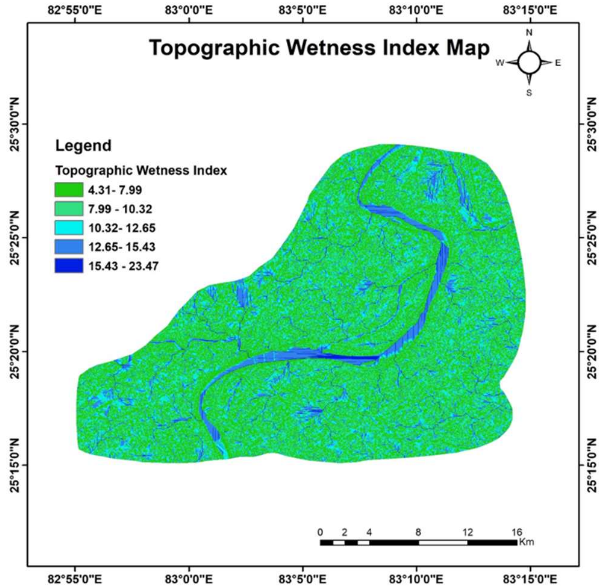

Fig. 10: Topographic wetness index map of the research area.

the land. The determination of the index is as follows:

$$TWI = \ln (a/\tan \beta) \quad \ldots(5)$$

The variable "a" represents the specific catchment area (SCA), which is an upslope area draining through a particular point per unit contour length. This area is equivalent to a specific grid cell width. On the other hand, "β" denotes the local slope. SCA can be evaluated in multiple ways (Beven & Kirkby.1979, Sörensen et al. 2006, Zhou et al. 2011). The topographic index is reclassified into five categories, such as 4.31–7.99, 7.99–10.32, 10.32–12.65, 12.65–15.43, and 15.43–23.47 which is shown in Fig. 10. A higher numerical value indicates a higher TWI, while a lower numerical value indicates a lower TWI.

GROUNDWATER POTENTIAL MAPPING AND VALIDATION

Various thematic layers, including LULC, geomorphology, geology, rainfall, soil, slope, drainage density, and TWI, have been generated through the spatial analyst tool within a GIS platform to find potential groundwater resources. Saaty's method for multi-criteria evaluation calculates the weights of different features and thematic layers, ranking them based on their individual importance in assessing groundwater potential. The resulting map categorizes groundwater potential areas into good, moderate, and poor classes which is demonstrated in Fig. 11.

An expanse displaying good groundwater potential spans 94.62 square kilometers, making up roughly 16.26% of the entire research area. The primary segment of this good potential zone is located alongside the Ganga River, featuring agricultural fields, abundant vegetation, and flood plains. The moderate groundwater potential zone, the most extensive section, covers 391.13 square kilometers, accounting for about 67.20% of the total research area. In contrast, the low groundwater potential zone encompasses 96.25 square kilometers, constituting approximately 16.54% of the research area. This zone is predominantly composed of urban areas characterized by alluvial plains, limited agricultural activity, and sparse vegetation, which is given in Table 8. During the fieldwork carried out in the pre and

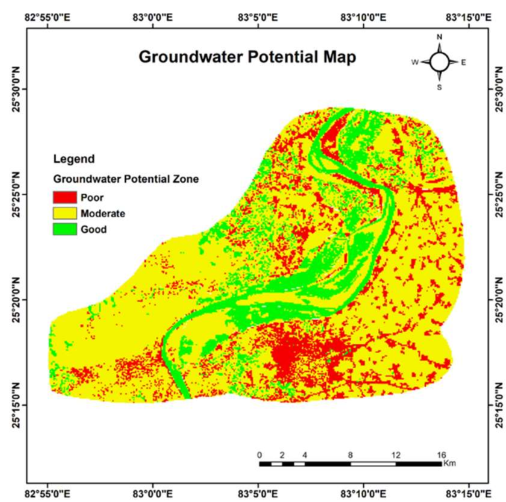

Fig. 11: Groundwater potential zone of the research area.

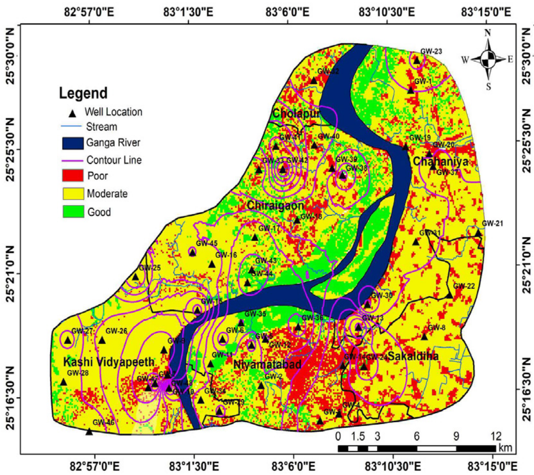

Fig. 12: Validation of the groundwater potential map with field data

Table 8: Groundwater potential zones.

GPZ	Area (km^2)	Area (In percentage)
Poor	96.25	16.54
moderate	391.13	67.20
Good	94.62	16.26

post-monsoon periods of 2022 and 2023, various water wells were observed to collect water level data. This water level data is used to validate the groundwater potential zones. The calculation of water level fluctuations involves assessing the variance between water levels before and after the monsoon season. Areas with low water level fluctuations show good groundwater potential, whereas areas with high water level fluctuations show low groundwater potential (Bera et al. 2020, Verma & Patel 2021, Kom et al. 2022). Using the Inverse Distance Weighting Method, contours with a 0.5-meter interval are superimposed on the GPZ map. Areas with dense contour lines show high water level fluctuations, and these are mostly urban and industrial areas. Consequentially, over-extraction of groundwater results in poor groundwater potential, whereas areas with low contour density represent low water level fluctuation, and this area is dominated by vegetation and agricultural fields, which results in good groundwater potential. The groundwater potential map of research area has been validated with field data as shown in Fig. 12.

The reliability of the findings was evaluated using the ROC curve. The ROC curve in Fig. 13 indicates a score of 0.88 (88%), which implies that the model achieves an average true positive rate (TPR) of 0.88 across all false positive rates (FPR). In simpler terms, the model correctly identifies 88% of the positive cases on average, even when accounting for false positives. This 0.88 value suggests that the model's performance in delineating the groundwater potential zones of the research area is excellent.

CONCLUSIONS

The research area comprises Varanasi and Chandauli districts, which are part of the Indo-Gangetic Plain. The rainfall pattern affects the groundwater potential zones in the research area. Areas experiencing high rainfall intensity tend to have higher groundwater potential zones, but this is influenced by various factors such as geology, geomorphology, land use and land cover (LULC), soil composition, slope, drainage density, and topographic wetness index (TWI). Geologically, the research area exhibits different lithologies including sand, silt, and clay. The aquifers exist in a multi-tier system in the research area. Sand possesses high porosity and permeability compared to silt, while clay is highly porous but lacks permeability. Therefore, sandstone forms a good aquifer, while clay forms a perched aquifer in some parts of the research area. Geomorphologically, the research

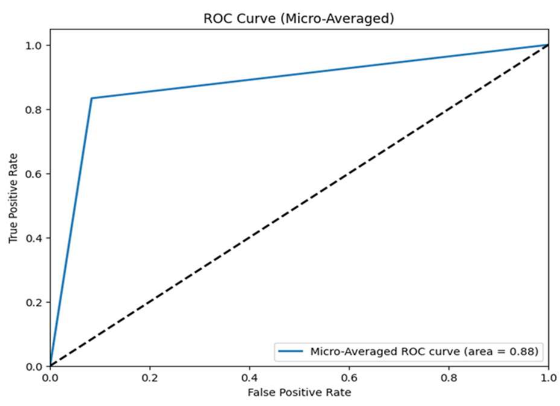

Fig. 13: The ROC curve.

area comprises water bodies (rivers, lakes, and ponds), floodplains, and alluvial plains. The areas occupied by water bodies exhibit good groundwater potential, followed by the floodplain and alluvial plain. The land use and land cover of the research area also influence groundwater potential. Areas characterized by impervious surfaces such as built-up areas, roads, and pavements have negligible percolation rates, resulting in low groundwater potential. Conversely, agricultural and forested areas exhibit high percolation rates, leading to good groundwater potential. Slope also plays an important role in groundwater potential mapping. Gentle slopes favor good groundwater potential, whereas steep slopes result in poor groundwater potential. The research area contains soil classified as orthic luvisols. All areas in the study exhibit similar soil types, resulting in consistent effects on water percolation rates. High drainage density leads to low groundwater potential, while areas with low drainage density represent groundwater potential zones. The topographic wetness index shows an opposite relationship to drainage density. All the factors have been combined using remote sensing and GIS. Different rankings have been assigned to various layers and sub-layers using the AHP method. Finally, a groundwater potential map has been generated, dividing the area into zones of good, moderate, and poor groundwater potential. As the research area is a rapidly growing city, the demand for water for various uses is increasing. Therefore, it is essential to map the different potentials of groundwater for sustainable development and management.

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REFERENCES

Ajay Kumar, V., Mondal, N. C. and Ahmed, S., 2020. Identification of groundwater potential zones using RS, GIS and AHP techniques: a case study in a part of Deccan volcanic province (DVP), Maharashtra, India. *Journal of the Indian Society of Remote Sensing*, 48, pp. 497-511. https://doi.org/10.1007/s12524-019-01086-3

Arkoprovo, B., Adarsa, J. and Prakash, S. S., 2012. Delineation of groundwater potential zones using satellite remote sensing and geographic information system techniques: a case study from Ganjam district, Orissa, India. *Research Journal of Recent Sciences*, 1(9), pp. 59-66.

Arulbalaji, P., Padmalal, D. and 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), p. 2082. https://doi.org/10.1038/s41598-019-38567-x

Avtar, R., Singh, C. K., Singh, G., Verma, R. L., Mukherjee, S. and Sawada, H., 2011. Landslide susceptibility zonation study using remote sensing and GIS technology in the Ken-Betwa River Link area, India. *Bulletin of Engineering Geology and the Environment*, 70, pp. 595-606. https://doi.org/10.1007/s10064-011-0368-5

Bera, A., Mukhopadhyay, B. P. and Barua, S., 2020. Delineation of groundwater potential zones in Karha river basin, Maharashtra, India, using AHP and geospatial techniques. *Arabian Journal of Geosciences*, 13, pp. 1-21. https://doi.org/10.1007/s12517-020-05702-2

Beven, K. J. and Kirkby, M. J., 1979. A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Journal*, 24(1), pp. 43-69. http://dx.doi.org/10.1080/02626667909491834

Bordoloi, A., Singh, K. K. and Gaichunglu, G., 2023. Application of analytical hierarchy process and GIS techniques to delineate the groundwater potential zones in and around Jorhat and Majuli areas of eastern Assam, India. *Modeling Earth Systems and Environment*, 9(2), pp. 1589-1612. https://doi.org/10.1007/s40808-022-01583-4

Central Ground Water Board (CGWB), 2021. Aquifer mapping and groundwater management plan, Varanasi district, Uttar Pradesh. Department of Water Resources, River Development and Ganga Rejuvenation, Ministry of Jal Shakti, Government of India. Available at: https://cgwb.gov.in/AQM/NAQUIM_REPORT/UP/VARANASI%20FINAL.pdf

Chowdhury, A., Jha, M. K., Chowdary, V. M. and Mal, B. C., 2009. Integrated remote sensing and GIS-based approach for assessing groundwater potential in West Medinipur district, West Bengal, India. *International Journal of Remote Sensing*, 30(1), pp. 231-250. https://doi.org/10.1080/01431160802270131

Dar, T., Rai, N. and Bhat, A., 2020. Delineation of potential groundwater recharge zones using analytical hierarchy process (AHP). *Geological Ecology and Landscapes*, 5(4), pp. 292-307. https://doi.org/10.1080/24749508.2020.1726562

Das, B. and Pal, S. C., 2020. Assessment of groundwater recharge and its potential zone identification in groundwater-stressed Goghat-I block of Hugli District, West Bengal, India. *Environmental Development and Sustainability*, 22(6), pp. 5905-5923. https://doi.org/10.1007/s10668-019-00457-7

Doke, A. B., Zolekar, R. B., Patel, H. and Das, S., 2021. Geospatial mapping of groundwater potential zones using multi-criteria decision-making AHP approach in a hardrock basaltic terrain in India. *Ecological Indicators*, 127, p. 107685. https://doi.org/10.1016/j.ecolind.2021.107685

Doke, A., Pardeshi, S. D., Pardeshi, S. S. and Das, S., 2018. Identification of morphogenetic regions and respective geomorphic processes: a GIS approach. *Arabian Journal of Geosciences*, 11, pp. 1-13. https://doi.org/10.1007/s12517-017-3358-5

Fan, Y., 2015. Groundwater in the Earth's critical zone: Relevance to large-scale patterns and processes. *Water Resources*, 51(5), pp. 3052-3069. https://doi.org/10.1002/2015WR017037

Gaur, S., Chahar, B. R. and Graillot, D., 2011. Combined use of groundwater modeling and potential zone analysis for management of groundwater. *International Journal of Applied Earth Observation and Geoinformation*, 13(1), pp. 127-139. https://doi.org/10.1016/j.jag.2010.09.001

Ghosh, S., Das, D., Gayen, S. K. and Bhardwaj, P., 2023. Delineation of groundwater potential zones using the AHP technique: a case study of Alipurduar district, West Bengal. *Modeling Earth Systems and Environment*, pp. 1-31. https://doi.org/10.1007/s40808-023-01733-2

Gleeson, T., Wada, Y., Bierkens, M. F. and Van Beek, L. P., 2012. Water balance of global aquifers revealed by groundwater footprint. *Nature*, 488(7410), pp. 197-200. https://doi.org/10.1038/nature11295

Gou, S., Gonzales, S. and Miller, G. R., 2015. Mapping potential groundwater-dependent ecosystems for sustainable management. *Groundwater*, 53(1), pp. 99-110.

Jaiswal, R. K., Mukherjee, S., Krishnamurthy, J. and Saxena, R., 2003.

Role of remote sensing and GIS techniques for generation of groundwater prospect zones towards rural development—an approach. *International Journal of Remote Sensing*, 24(5), pp. 993-1008. https://doi.org/10.1080/01431160210144543

Janardhana Raju, N., Shukla, U. K. and Ram, P., 2011. Hydrogeochemistry for the assessment of groundwater quality in Varanasi: a fast-urbanizing center in Uttar Pradesh, India. *Environmental Monitoring and Assessment*, 173, pp. 279-300. https://doi.org/10.1007/s10661-010-1387-6

Jha, M. K., Chowdary, V. M. and Chowdhury, A., 2010. Groundwater assessment in Salboni Block, West Bengal (India) using remote sensing, geographical information system and multi-criteria decision analysis techniques. *Hydrogeology Journal*, 18(7), pp. 1713-1728. https://doi.org/10.1007/s10040-010-0631-z

Kom, K. P., Gurugnanam, B. and Sunitha, V., 2022. Delineation of groundwater potential zones using GIS and AHP techniques in Coimbatore district, South India. *International Journal of Energy and Water Resources*, pp. 1-25. https://doi.org/10.1007/s42108-022-00188-y

Kumari, A. and Singh, A., 2021. Delineation of groundwater potential zone using analytical hierarchy process. *Journal of the Geological Society of India*, 97, pp. 935-942. https://doi.org/10.1007/s12594-021-1794-z

Lerner, D. N. and Harris, B., 2009. The relationship between land use and groundwater resources and quality. *Land Use Policy*, 26, pp. S265-S273. https://doi.org/10.1016/j.landusepol.2009.09.005

Machiwal, D., Jha, M. K. and Mal, B. C., 2011. Assessment of groundwater potential in a semi-arid region of India using remote sensing, GIS and MCDM techniques. *Water Resources Management*, 25, pp. 1359-1386. https://doi.org/10.1007/s11269-010-9749-y

Maity, D. K. and Mandal, S., 2019. Identification of groundwater potential zones of the Kumari River basin, India: an RS & GIS based semi-quantitative approach. *Environmental Development and Sustainability*, 21, pp. 1013-1034. https://doi.org/10.1007/s10668-017-0072-0

Melese, T. and Belay, T., 2021. Groundwater potential zone mapping using analytical hierarchy process and GIS in Muga Watershed, Abay Basin, Ethiopia. *Global Challenges*, 6(1), p. 2100068. https://doi.org/10.1002/gch2.202100068

Moges, D. M., Bhat, H. G. and Thrivikramji, K. P., 2019. Investigation of groundwater resources in highland Ethiopia using geospatial technology. *Modeling Earth Systems and Environment*, 5, pp. 1333-1345. https://doi.org/10.1007/s40808-019-00603-0

Murmu, P., Kumar, M., Lal, D., Sonker, I. and Singh, S. K., 2019. Delineation of groundwater potential zones using geospatial techniques and analytical hierarchy process in Dumka district, Jharkhand, India. *Groundwater for Sustainable Development*, 9, p. 100239. https://doi.org/10.1016/j.gsd.2019.100239

Murthy, K. S. R., 2000. Ground water potential in a semi-arid region of Andhra Pradesh - a geographical information system approach. *International Journal of Remote Sensing*, 21(9), pp. 1867-1884. https://doi.org/10.1080/014311600209788

Nanda, S., Annadurai, R. and Barik, K. K., 2017. Geospatial decipherment of groundwater potential of Kattankolathur block of Tamil Nadu using MCDM techniques. *Remote Sensing Applications: Society and Environment*, 8, pp. 240-250. https://doi.org/10.1016/j.rsase.2017.10.002

Nandimandalam, J. R., 2012. Evaluation of hydrogeochemical processes in the Pleistocene aquifers of middle Ganga Plain, Uttar Pradesh, India. *Environmental Earth Sciences*, 65, pp. 1291-1308. https://doi.org/10.1007/s12665-011-1377-1

Pande, C. B., Moharir, K. N., Singh, S. K. and Varade, A. M., 2020. An integrated approach to delineate the groundwater potential zones in Devdari watershed area of Akola district, Maharashtra, Central India. *Environmental Development and Sustainability*, 22, pp. 4867-4887. https://doi.org/10.1007/s10668-019-00409-1

Parameswari, K. and Padmini, T. K., 2018. Assessment of groundwater potential in Tirukalukundram block of southern Chennai Metropolitan Area. *Environmental Development and Sustainability*, 20, pp. 1535-1552. https://doi.org/10.1007/s10668-017-9952-6

Prasad, R. K., Mondal, N. C., Banerjee, P., Nandakumar, M. V. and Singh, V. S., 2008. Deciphering potential groundwater zone in hard rock through the application of GIS. *Environmental Geology*, 55, pp. 467-475. https://doi.org/10.1007/s00254-007-0992-3

Raduła, M. W., Szymura, T. H. and Szymura, M., 2018. Topographic wetness index explains soil moisture better than bioindication with Ellenberg's indicator values. *Ecological Indicators*, 85, pp. 172-179. https://doi.org/10.1016/j.ecolind.2017.10.011

Saaty, T. L., 1980. *The analytical hierarchy process: Planning, priority, resource allocation*. RWS Publications, USA.

Saaty, T. L., 1990. How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*, 48(1), pp. 9-26. https://doi.org/10.1016/0377-2217(90)90057-I

Saravanan, S., Saranya, T., Abijith, D., Jacinth, J. J. and Singh, L., 2021. Delineation of groundwater potential zones for Arkavathi sub-watershed, Karnataka, India using remote sensing and GIS. *Environmental Challenges*, 5, p. 100380. https://doi.org/10.1016/j.envc.2021.100380

Senapati, U. and Das, T. K., 2022. GIS-based comparative assessment of groundwater potential zone using MIF and AHP techniques in Cooch Behar district, West Bengal. *Applied Water Science*, 12(3), p. 43. https://doi.org/10.1007/s13201-021-01509-y

Shaban, A., Khawlie, M. and Abdallah, C., 2006. Use of remote sensing and GIS to determine recharge potential zones: the case of Occidental Lebanon. *Hydrogeology Journal*, 14, pp. 433-443. https://doi.org/10.1007/s10040-005-0437-6

Shekhar, S. and Pandey, A. C., 2014. Delineation of groundwater potential zone in hard rock terrain of India using remote sensing, geographical information system (GIS) and analytic hierarchy process (AHP) techniques. *Geocarto International*, 30(4), pp. 402-421. https://doi.org/10.1080/10106049.2014.894584

Sörensen, R., Zinko, U. and Seibert, J., 2006. On the calculation of the topographic wetness index: evaluation of different methods based on field observations. *Hydrology and Earth System Sciences*, 10(1), pp. 101-112. https://doi.org/10.5194/hess-10-101-2006

Sternberg, T. and Paillou, P., 2015. Mapping potential shallow groundwater in the Gobi Desert using remote sensing: Lake Ulaan Nuur. *Journal of Arid Environments*, 118, pp. 21-27. https://doi.org/10.1016/j.jaridenv.2015.02.020

Tamiru, H. and Wagari, M., 2021. Evaluation of data-driven model and GIS technique performance for identification of groundwater potential zones: A case of Fincha Catchment, Abay Basin, Ethiopia. *Journal of Hydrology: Regional Studies*, 37, p. 100902. https://doi.org/10.1016/j.ejrh.2021.100902

Thapa, R., Gupta, S., Guin, S. and Kaur, H., 2017. Assessment of groundwater potential zones using multi-influencing factor (MIF) and GIS: a case study from Birbhum district, West Bengal. *Applied Water Science*, 7, pp. 4117-4131. https://doi.org/10.1007/s13201-017-0571-z

Verma, N. and Patel, R. K., 2021. Delineation of groundwater potential zones in lower Rihand River Basin, India using geospatial techniques and AHP. *Egyptian Journal of Remote Sensing and Space Sciences*, 24(3), pp. 559-570. https://doi.org/10.1016/j.ejrs.2021.03.005

Walmsley, A., Azadi, H., Tomeckova, K. and Sklenicka, P., 2020. Contrasting effects of land tenure on degradation of Cambisols and Luvisols: The case of Central Bohemia Region in the Czech Republic. *Land Use Policy*, 99, p. 104956. https://doi.org/10.1016/j.landusepol.2020.104956

Yeh, H. F., Cheng, Y. S., Lin, H. I. and Lee, C. H., 2016. Mapping groundwater recharge potential zone using a GIS approach in Hualian

River, Taiwan. *Sustainable Environment Research*, 26(1), pp. 33-43. https://doi.org/10.1016/j.serj.2015.09.005

Zhou, G., Wei, X., Wu, Y., Liu, S., Huang, Y., Yan, J. and Liu, X., 2011. Quantifying the hydrological responses to climate change in an intact forested small watershed in Southern China. *Global Change Biology*, 17(12), pp. 3736-3746. https://doi.org/10.1111/j.1365-2486.2011.02499.x

Zhu, Q. and Abdelkareem, M., 2021. Mapping groundwater potential zones using a knowledge-driven approach and GIS analysis. *Water*, 13(5), p. 579. https://doi.org/10.3390/w13050579