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RESEARCH PAPER

Comparative Analysis of Remote Sensing-based Models for Determining The Groundwater Potential Zone Mapping

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Abstract

The maintenance of ecological diversity, public health, and economic expansion depends on appropriately managing groundwater supplies. This study focuses on the Markanda Watershed, a region characterized by its diverse topography, and pressing issues such as groundwater over-extraction, seasonal water shortages, and flooding. The analytic hierarchy process (AHP) and fuzzy AHP are two highly developed techniques and scientific ideas used in this work to discover groundwater potential zones (GWPZs). The GWPZs are determined employing 12 thematic layers. Using both approaches, these thematic maps are weighted based on their characteristics and water potential. Upon analysis with the AHP and Fuzzy-AHP, four zones – low 0.034% (0.0124 km^2) and 13.535278% (4.8727km^2), moderate 44.59% (16.0532 km^2) and, 37.17% (13.3812km^2), high 52.923% (19.0523 km^2) and 42.2575% (15.21217km^2) and very high 2.450% (0.8821 km^2) and 7.0372222% (2.5334 km^2) were revealed in this study that indicate different levels of groundwater potential. Validation through Receiver Operating Characteristics (ROC) analysis indicates that the Fuzzy-AHP model achieves an accuracy of 76.3%, compared to 71.43% for the AHP model. Based on the study's findings, a targeted groundwater management plan is proposed to optimize resource use and sustainability. High-potential zones should be prioritized for groundwater extraction and recharge. Moderate-potential areas require a balanced approach. Low-potential zones should focus on reducing groundwater dependence and enhancing surface water storage to prevent overexploitation. These strategies aim to ensure sustainable groundwater management, promote ecological balance, and support socio-economic development.

Keywords: Hydrology; Groundwater shortage; Sustainable drinking water; Remote Sensing; Overlay analysis.

1. Introduction

Life on Earth is fundamentally dependent on water, making it the most essential and widely consumed material [1], [2]. Unfortunately, a substantial percentage (97%) of Earth's water is salinized, making it unsuitable for human use [3], [4]. Only 3% is considered freshwater, which humans rely on for drinking and other essential needs [5]. Among the kinds of freshwater resources is groundwater, which is defined as water stored in aquifers beneath the earth's surface [6]. It makes up more than a third of the world's freshwater supply. It serves as the main source of fresh water and is considered to be less contaminated than other water supplies. Approximately fifty percent of the easily accessible freshwater for everyday cleaning, drinking, and cooking is obtained from it [7]. Groundwater is widely used in many parts of the world for agricultural, industrial, and residential purposes [8], [9]. For around 2.5 billion people globally, it provides a vital source of water that meets their needs for domestic use [10]. Groundwater is India's most important natural resource for sustainability due to its dependence on agriculture [11], [12]. Groundwater is an essential component of the economy, but mismanagement of groundwater, industrialization, inappropriate investigations, and human population growth have turned this precious energy source into a major problem [13]. Therefore, to meet the growing demand for groundwater, both for the current generation and for future generations, it is imperative to develop efficient delineation techniques and apply sustainable groundwater management strategies [5]. Sustaining groundwater quality and guaranteeing the effectiveness of the groundwater management system depends on the identification of prospective zones for groundwater recharge.

Forecasting the potential recharge zone can be challenging because groundwater is usually an invisible source [13], [14]. Researchers have used various field survey techniques, such as geological, geophysical, and hydrological studies, to identify possible groundwater zones [15]. These techniques can be time-consuming and require a large financial and human resource budget. However, with technology, GWPZs can be efficiently identified by utilizing GIS, RS, weighted AHP, and fuzzy AHP, among other techniques. The GWPZ can be mapped using GIS, RS, weighted AHP, and similar techniques. Researchers have successfully used such techniques in multiple projects including the Guigou basin in Morrocco [16], the Nambiyar River basin in Tamil Nadu [17], a large watershed in southern Saudi Arabia [18], and the Arghandab River basin, Afghanistan [19]. The combination of GIS, RS, and AHP techniques is used for identifying areas with varying groundwater probability in categories: very high, high, moderate, low, and shallow zones. Appendix A presents various layers/parameters utilized by different studies in their GIS and RS-based groundwater potential mapping. Commonly used layers in these studies were slope, rainfall, soil, drainage density, lineament density, LULC, and geology. Appendix B showcases the different methodologies employed in the studies for groundwater potential mapping. The most common methods used in the summarized studies were Weighted overlay Analysis, AHP, and Fuzzy Logic. Studies that solely utilized AHP include [1], [18], Fuzzy [20], and TOPSIS [21]. While few studies used combined methods [22]. In this study weighted AHP and Fuzzy AHP approaches are employed to assess the weights of thematic layers depending on their attributes and the function of groundwater related to the water potential. This contributes to the accurate identification of GWPZs. These methods help to understand for rationalization and planning of these resources management and water resources [23]. Furthermore, the GWPZ map generated by Fuzzy-AHP demonstrates greater reliability compared to the one created by AHP, as it integrates Fuzzy logic to address the uncertainties and imprecisions that are intrinsic to decision-making processes. To tackle possible consistency challenges when employing the AHP method for pairwise comparisons of criteria, it is essential to examine the logical consistency of the derived weights [24]. To address these challenges, initially proposed Fuzzy-AHP [25]. The integration of Fuzzy logic into AHP effectively addresses hierarchical Fuzzy multi-criteria decision-making scenarios. Controversies arising in knowledge-driven AHP can be resolved through the application of the fuzzy AHP method, which incorporates subjective judgments [25]. AHP and Fuzzy-AHP have been applied in various studies for groundwater potential mapping, demonstrating the effectiveness of these methods. Both AHP and Fuzzy-AHP have proven to be reliable techniques for assessing groundwater potential. These techniques allow for the identification of potential groundwater zones and offer essential data for the management and decision-making regarding water resources. The methods effectively manage the complexity of MCDM and tackle the inherent uncertainties in the decision-making process. They also account for the vagueness by assessing the relative importance of criteria and alternatives [26]. The weighted AHP approach and the fuzzy AHP method classify potential zones differently, with different percentages being allocated to very high, high, moderate, and poor potential areas. The efficiency of these approaches, however, is verified also by methods such as ROC analysis and checking the result with currently available groundwater information used as a basis for sustainable management of groundwater resources and planning [27].

The Markanda Watershed is located in Himachal Pradesh Haryana and Punjab and the following problems related to groundwater have been identified and recognized, the problem of over-extraction, the problem of water shortage due to seasonal variations, and the problem of flooding. These problems are compounded by the region's diverse topography and varying climatic conditions, making it a representative area for studying groundwater management issues in semi-arid and flood-prone regions of India [28]. The purpose of this study is to provide important insights into sustainable groundwater management systems through the application of GIS and remote sensing coupled with AHP and Fuzzy AHP techniques and from the identified research gap. This work will enable the identification of areas that have potential sources of groundwater or those that can be used to recharge existing water sources hence addressing the equity issue associated with distribution and usage of water [29]. The relevance of this research is in the development of governmental actions and recommendations in case of water management problems and the enhancement of local authorities' strategies. Through employing these analytical tools, the study seeks to increase water security, raise the productivity of agriculture, and support environmental management strategies. Present methods that use integrated RS, and GIS, with different methods including, weighted AHP and Fuzzy-AHP techniques to identify and delineate GWPZs in the watershed. Reveal groundwater mapping abilities using geographic information technologies. To provide insights into the strengths, weaknesses, and practical implications of each methodology for finding groundwater resource management. The novelty of this study lies in the integrated use of GIS, and RS techniques with the AHP and Fuzzy-AHP models. While traditional studies often rely on standard GIS and AHP methods to map GWPZs, they may not fully account for the uncertainties in data interpretation. The incorporation of Fuzzy-AHP allows for a more nuanced and precise identification of GWPZs by addressing these uncertainties. Additionally, no GWPZ study in this area utilizes GIS and RS. The study's findings are crucial for shaping governmental policies and local strategies, ensuring equitable water distribution, improving agricultural productivity, enhancing water security, and supporting environmental management in the Markanda Watershed and similar regions.

2. Materials and method

2.1 Study Area

The location of the Markanda Watershed is shown in Figure 1. It originates in the Shivalik Hills of Himachal Pradesh and flows through Haryana. The watershed includes various tributaries and drains into the Ghaggar-Hakra River system. The watershed has a dendritic to sub-dendritic drainage pattern and extends 30°01 N to 30°43 N latitudes and 76°24 E to 77°24 E longitudes [30]. The river originates in the Sirmour District of Himachal Pradesh (333 km^2) on the southern slopes of the Siwalik Himalayas. It then flows in an easterly direction through the alluvial plains of Haryana (2189 km^2) and Punjab (174 km^2), before merging with the Ghaggar River. The surface area has an average slope of roughly 5°, ranging from extremely mild (0°) to extremely steep (60°). Due to the varied land elevations, including steep slopes, and low-lying plains, the watershed will make an interesting study on finding ground potential zones using GIS and remote sensing methods integrated by AHP and Fuzzy-AHP (Figure 1).

2.2 Data Used

The purpose of this study is to identify the potential zone of groundwater availability in the Indian Watershed. Different datasets are utilized to generate the various parameters used in this research. The present study employs two datasets: organization ground data and RS data. The relevant national and international research platforms provided satellite and ground data to develop the twelve significant groundwater potential measures (Table 1).

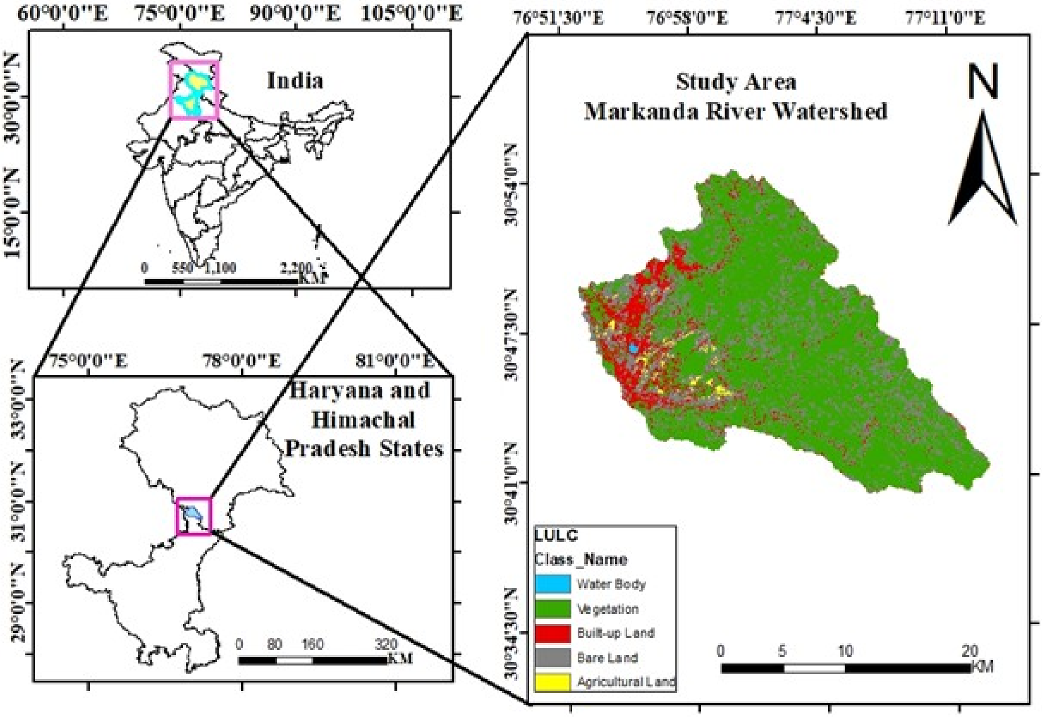

Figure 1: *Location of the study area with LULC classification map of the studied watershed.*

2.3 Methodology

The study was organized into four stages: 1) The groundwater inventory map of the study area was prepared using a variety of geospatial. 2) Twelve influential groundwater parameters were generated. 3) Two geospatial models, including AHP, and Fuzzy AHP, were used to generate the GWPZ. 4) Finally, validation was carried out using the AUC method for evaluating accuracy (Figure 2).

2.4 Selection of Influential Parameters for Groundwater Potential Zonation

According to the researchers, conditioning parameters should be carefully selected as they have a substantial impact on the GWPZ final output map while considering groundwater potential into account [31]. Several factors impact the existence and generation of groundwater beneath a designated aquifer. To assess the effects of the mentioned features on groundwater potential in the study area, twelve key conditioning factors including elevation, slope angle, aspect, curvature, drainage network, rainfall, LULC, soil, and NDVI, are considered in this study (Figure 3).

Soil is a key component for defining GWPZs. This is because it is the uppermost layer of land and critical role in water infiltration. Soil type, thickness, texture, and composition impact infiltration

Table 1: *Applied datasets were used to calculate the GWPZ.*

Sl. No	Data	Data Source	Data Availability	Scale or resolution
1	Soil	FAO soil classification (1988)		
2	DEM (Slope, Aspect, Curvature, Twi, TPI, Lineament Density, Elevation, and Drainage Density)	USGS Earth Explorer (https://earthexplorer.usgs.gov/)		30
3	Landsat (LULC, NDVI)			30
4	Station Data (Rainfall)			30

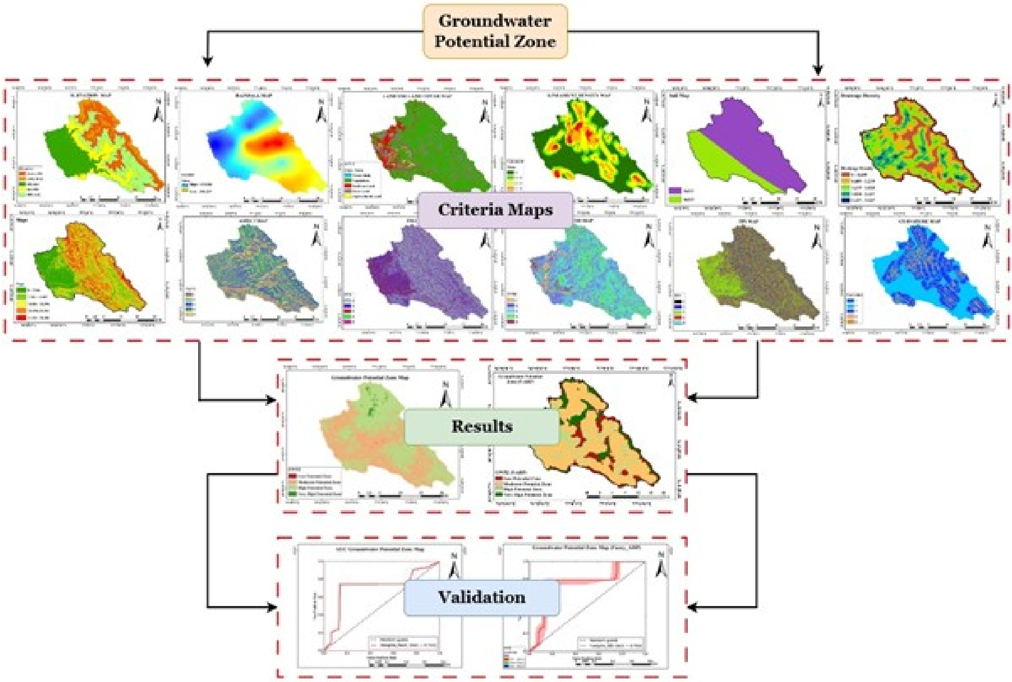

Figure 2: *Adopted method for calculating the GWPZ in the studied watershed.*

and groundwater recharge, making it a crucial factor in determining GWPZs [32]. Geomorphology, geology, relief, time, and other factors all affect the types, features, and distribution of soil in a particular area. The pore spaces within the soil influence the penetration capability of water into the subsurface, ultimately impacting groundwater availability [33]. The soil type and classification map of the research Slope is one of the most fundamental factors influencing the groundwater potential is the slope. Groundwater potential typically increases with decreasing slope values [34]. Flat places with low slopes can hold precipitation and recharge groundwater, while higher parts with steep slopes have high runoff and minimal infiltration [35]. The slope map for the watershed was generated using a 30 m resolution DEM derived from SRTM data. The slope 8 (degrees) values were categorized into five categories: fat (1), gentle (1–2), medium (2–3), steep (3–4), and very steep (4–5). Fat and gentle slopes are given more weight. For slopes that are steep as well as very steep, a low weight is

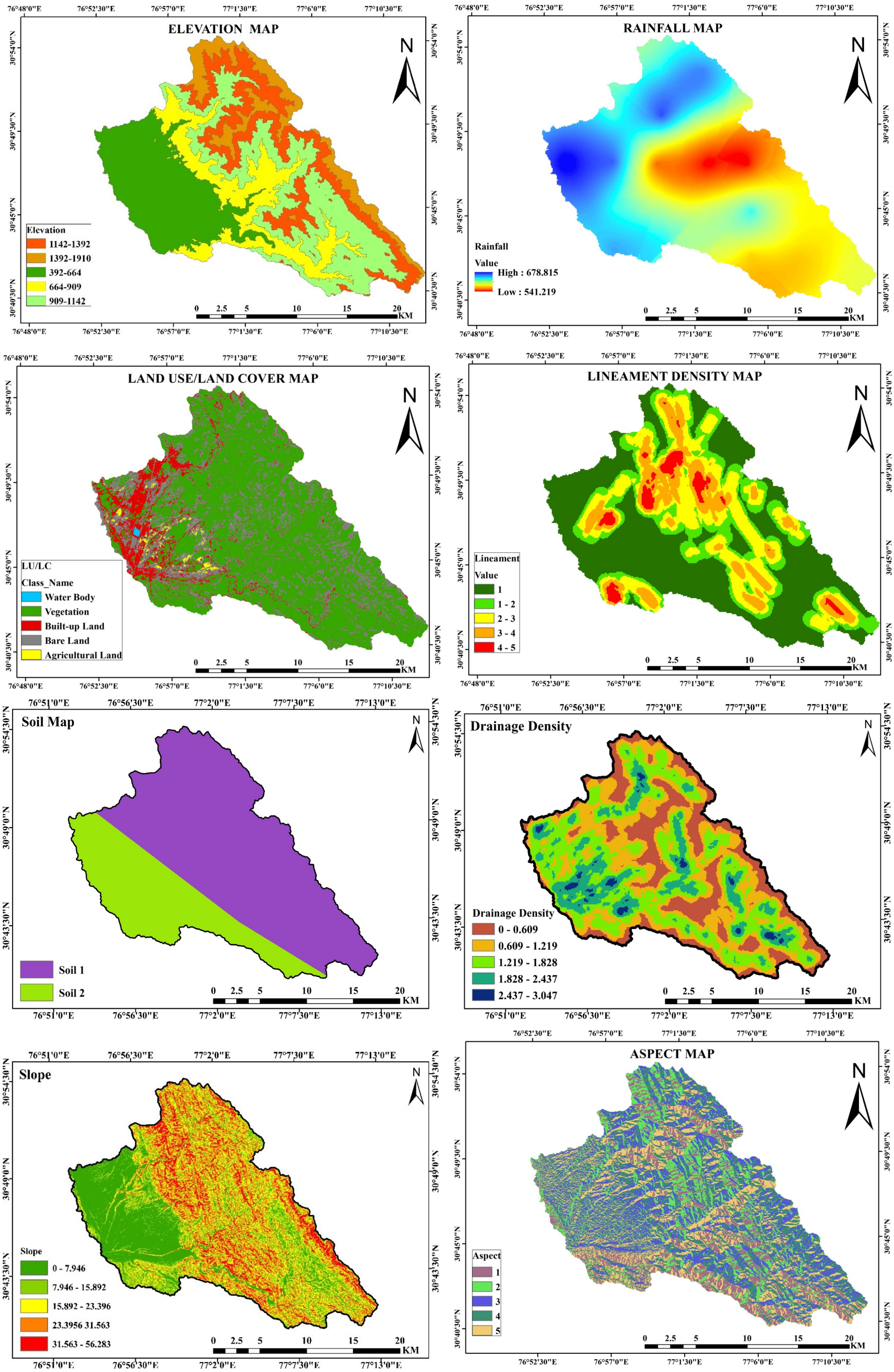

Figure 3: *Criteria maps of the study area.*

provided (Figure 3).

$$\text{Step 1 (Flow Accumulation}^{*}\text{ 10 }^{*}\text{)Tan(Slope in degree}^{*}\text{ 0.017453)} \tag{1}$$

$$\text{Step 2 Ln (Flow Accumulation } * 10 * \text{Tan(Slope in degree}^{*}\text{ 0.017453)} \tag{2}$$

$$\text{Step 3 Ln (Flow Accumulation } + 0.001) * \left(\left(\text{Slope in } \frac{\text{Degree}}{100}\right) + 0.001\right. \tag{3}$$

$$\text{Step 4(Flow Accumulation+1}^{*}\text{10)} * \text{Tan (Slope in degree)} \tag{4}$$

$$\text{Step 5(Flow Accumulation}^{*}\text{Tan(Slope in degree)} \tag{5}$$

Drainage Density refers to the length of a stream per unit area within a watershed [36]. It measures the average spacing and proximity of stream channels across a basin, producing an estimate of their density [37]. Observations of drainage density across geological and climatic conditions show that places with permeability beneath the soil, dense vegetative cover, and low relief tend to have low drainage density. Low vegetative cover, impermeable material, and hilly landscape all contribute to high drainage density [38]. The drainage density is classified into different categories: very low 21.6% (100.7km^2), low 26.6% (142 km^2), moderate 15.02% (70km^2), high 24,4% (113.7km^2), and very high 12.3% 57.5 km^2). The Yellow Part is an indicator of checking the exact area of DD in the ArcMap.

Lineament Density is the topographic characteristics of a landscape (lineaments) that significantly influence hydrological processes, including water flow, storage, and infiltration into the subsurface [39]. Groundwater recharge systems, as well as movement directions, are controlled by fracture and fault systems. One example of a hydrogeology application is the acquisition and analysis of soil composition data from satellite images, and other structural elements, including fractures, which might occasionally operate as drains and contribute to groundwater recharge. According to Shaban, linked lineaments let groundwater flow along a subsurface channel [40]. Due to this, these can be used as an analytical criterion when creating maps of possible water recharge areas and as an indicative parameter of groundwater movement [41].

Rainfall is one of the major hydrologic components that has been standardized as a significant base of aquifer recharge and a primary source of groundwater availability, particularly in arid locations [42]. Rainfall is a key source of groundwater recharge and a critical aspect of the water cycle [43]. Rainfall distributions affect groundwater recharge both spatially and temporally. Increased rainfall tends to raise groundwater potential. In areas with low rainfall, groundwater recharging may be limited. Rainfall duration and intensity affect infiltration. Fast, high-intensity rain increases surface runoff while decreasing infiltration, whereas low-intensity, long-duration rain has a greater impact on infiltration. High rainfall contributes to higher weights and vice versa (Figure 3).

Land Use Land Cover (LULC) is a key factor affecting groundwater recharge, occurrence, and availability. LULC analyses environmental characteristics that impact groundwater penetration and surface runoff [31]. Groundwater potential is typically lower in bare and built-up areas, but higher in vegetation and near water reservoirs. Sentinel-2 data is used in GEE to generate a LULC map of the Markanda watershed using a machine-learning method. The causative component was classified into five classes to assess its impact on groundwater. The research area's current land-use/cover pattern was developed using Landsat ETM+ images from March 18, 2024. The watershed of this study area has various LULC topographies, including built-up land (39.1km^2), bare land (109.7 km^2), agricultural land (3.55 km^2), water bodies (0.421 km^2), and vegetation areas (285.3 km^2).

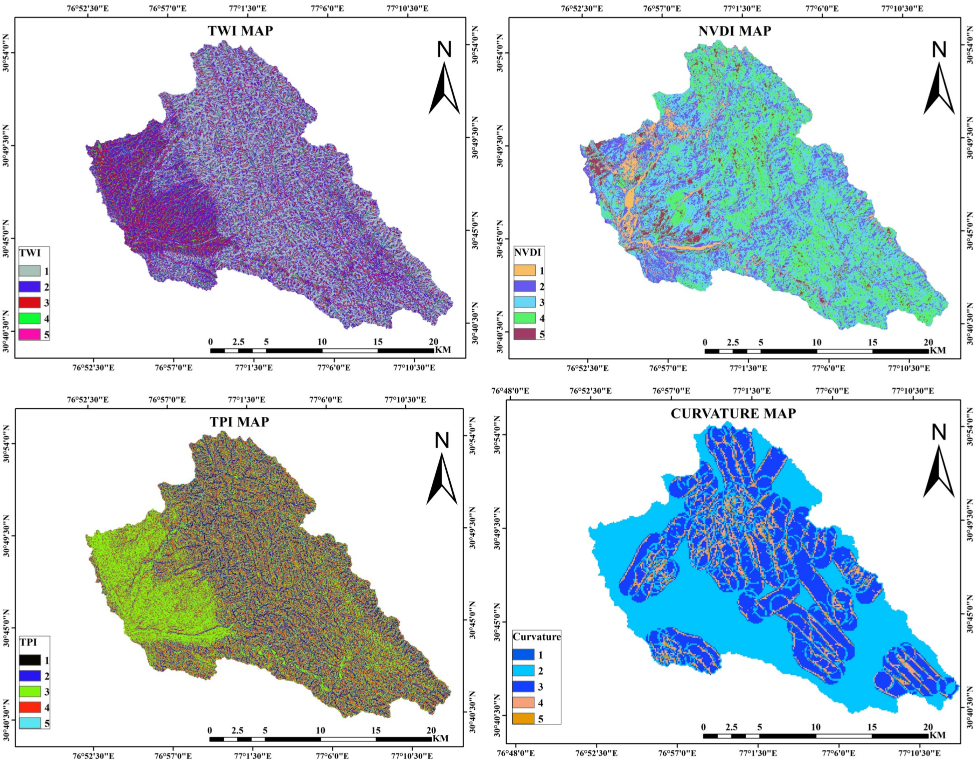

Figure 4: *Criteria maps of the study area.*

Elevation is a crucial factor for identifying possible groundwater areas. Altitude affects the potential GWPZ and is conversely related to the reservoir [44]. The elevation of this study enables us to decide the optimal position in GWPZs. The elevation map study area was generated using ASTER-DEM in ArcGIS software 10.8. This research examined the contribution of the Markanda Watershed to groundwater potential regions across five elevation classes (Figure 3). The elevation information for the research region was obtained using SRTM-DEM. The DEM was divided into five groups based on elevation ranges: very low (10.3 km^2), low 6.8 km^2), moderate (10.6 km^2), high (7.6 km^2), and extremely high (4.2 km^2). The use of this classification helps better understanding and analysis of elevation changes in the studied area. Groundwater potential zoning identified low-elevation areas were given a higher weightage, based on their potential, while high-elevation areas received a lower weightage. This weighting approach evaluates groundwater potential across various elevation zones (Figure 3).

Curvature of the ground surface influences water accumulation, infiltration rate, and overflow. It indicates the ability to store and retain water reserves on the surface [45]. Dipped structures typically hold more water (Figure 4).

Aspect is the slope aspect impacts precipitation, sun radiation, wind speed, and LULC, affecting water penetration to sediments and groundwater potential in the region [46]. The aspect existing region is categorized into five groups (Figure 3).

NVDI is a widely used parameter in GWPZs [41]. There is a parallel relationship between NDVI and groundwater. For example, as the region's plant density expands the groundwater table declines and vice versa. The NDVI of the Markanada watershed is calculated from Sentinel-2. The final NDVI map was reclassified into five classes in the GIS environment, as shown in (Figure 4).

$$NDVI = \frac{NIR - R}{NIR + R} \tag{6}$$

The bands of these wavelengths are called Red and NIR. The L value fluctuates with the amount of green plant cover.

TWI It is a secondary topographic parameter that is used to highlight topographic influences on the position and ability of runoff as well as infiltration capabilities [47] and thus groundwater occurrence [48].

$$\mathrm{TWI} = \ln\left(\frac{\alpha}{\tan\beta}\right) \tag{7}$$

Where, α is the upslope contributing area per unit contour length, β is the slope angle/gradient and combined $tan\beta$ represents the frequency distributions of slope/ steepest downslope direction.

2.5 AHP analysis

After creating theme layers for groundwater modeling, the factors' impact on aquifer replenishment [49]. The AHP is largely regarded as a reliable procedure for making multicriteria and decision-making [50], and it was used to create the matrix. This approach generates a hierarchical structure by assigning weight values to each criterion or sub-criteria during decision-making [51]. During the decision-making process, analytical approaches were used to quantify the design requirements and elements using a paired technique [52]. This technique utilizes a pairwise comparison matrix to determine individual weighted scores for each criterion, ultimately normalizing the sum of these factors to 1 [53]. In this study, AHP was employed to calculate weight scores for the established criteria. Following Saaty's method [54], a pairwise comparison matrix was developed. This matrix utilized a scoring system ranging from 1 to 9, where 9 signified extreme significance and 1 indicated equal importance (Appendix C-E). The number of comparisons within the pairwise matrix is mathematically derived based on the formula $n = \left(\frac{n-1}{2}\right)$, where n represents the total number of criteria considered for site selection [55]. Once the pairwise matrix was established, weight calculations were performed using the Saaty method [56]. Equation 8 calculates the consistency ratio (CR), which is used to estimate the analytical hierarchy process. This formula aids in determining the modified logical contradiction of the pairwise comparison matrix created using professional judgment or experience.

$$CR = \left(\frac{CI}{RI}\right) \tag{8}$$

where CI indicates the consistency index and RI indicates random index.

$$CI = \frac{(\lambda_{\max} - n)}{(n - 1)} \tag{9}$$

$$\mathrm{CI} = \frac{(13.6 - 12)}{(12 - 1)} = 0.14 \tag{10}$$

$$\mathrm{CR} = \frac{(0.14)}{(1.48)} = 0.097 \tag{11}$$

Each pair of criteria was ranked according to its relative value to construct the matrix. To signify equivalent weights with the other diagonal elements, the diagonal parts of the matrix were set to 1. When $\lambda_{\max}$ is the highest eigenvector of the computed matrix and n is the number of criteria, equations 9-11 show the consistency index (CI). Random index (RI) is the mean value of the consistency index depending on the matrix.

ArcGIS's weighted overlay analysis proved to be an effective method for mapping the GWPZs with the weighted features into consideration. The study considered several thematic levels, giving each weight according to their significance in figuring out the groundwater potential. Elevation was the most significant signal among the thematic layers, carrying a weight of 22%. This indicates that there is a greater chance of having desirable groundwater potential in low-elevation areas. With weights of 14, 13, 10, and 10%, respectively, it was found that soil, LULC, rainfall, lineament density, and elevation had the next highest levels of influence. However, curvature, NDVI, and TPI which have weights of 2, 2, and 3%, respectively were considered to have the least influence on the identification of groundwater recharge zones. A groundwater potential map was created using GIS by combining multiple thematic layers that support the existence of groundwater. This study uses thematic maps for GWPZ mapping, with weights set by AHP and Fuzzy-AHP with validation.

2.6 Fuzzy AHP

Fuzzy set theory is a useful modeling tool for multi-criteria decision issues. The conventional AHP approach provides the foundation for the fuzzy AHP technique. and is applied to address decision-making problems with several criteria [57]. Many studies have attempted to use the fuzzy clustering concept and hierarchical structure analysis for the alternative selection in the literature to identify the optimal choice in multi-criteria decision-making [58]. The current study compared and used the fuzzy version of the logarithmic least squares [59] to determine the fuzzy rates represented by triangular fuzzy numbers (TFNs). Subsequently, other studies frequently used the approach for decision-making problems and made modifications to the approach [60], [61]. Fuzzy-AHP allows factors to be compared and their relative importance to be determined, which makes managing difficult decisions easier. Researchers suggest that integrating Fuzzy-AHP into multi-criteria decisions improves the accuracy of groundwater potential mapping [49]. As a subfield of artificial intelligence, fuzzy logic uses approximate reasoning instead of precise computations. It offers a mathematical framework for dealing with uncertainty and ambiguity by accepting that things can be partially true or untrue and allowing degrees of truth to be described mathematically. This study considered twelve distinct theme layers. Experts used Saaty's scale to assign weights to criteria (1–9). When it comes to GWPZs, a low-weight parameter has little influence and a high-weight parameter has a big impact. For example, equal importance in AHP is represented by the number 1, whereas in Fuzzy-AHP, it is represented by the numbers 1, 1, and 1 for the lower, middle, and upper triangle values (Appendix F). Values 1, 2, 3, and 5 and 6 are transformed into fuzzy numbers in Appendix C-E AHP pairwise comparison matrix (using '1' as an example of 1,1,1). The reciprocals of the half, third, fifth, and sixth are not directly convertible into fuzzy numbers. Equation 12 can be used to find the reciprocal fuzzy number.

$$A^{-1} = (l, m, u)^{-1} = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right) \tag{12}$$

where u stands for upper, m for middle, and l for lower. Equation 3 transforms the reciprocal value 1/2, which is written as in Appendix C second and third rows, into a fuzzy number. $A^{-1} = (1, 2, 3)^{-1} = \left(\frac{1}{3}, \frac{1}{2}, \frac{1}{1}\right)$........... In the same way, Appendix G displays the residual reciprocal values following their conversion to fuzzy numbers. Using Buckley's [62] geometric mean technique, the fuzzy geometric mean, and the fuzzy weights of each criterion were determined.

The subsequent step is to figure out Equation 4 to determine the fuzzy geometric mean value, ri, as follows:

$$A1 * A2 = (l1, m1, u1) * (l2, m2, u2) = (l1 * l2, m1 * m2, u1 * u2) \tag{13}$$

The following formula is used to determine the fuzzy geometric mean value in Appendix G, row 2, and columns 2, 3, and 4.

$$r_i = (1 * 3 * 4 * 2 * 3 * 3 * 1 * 2 * 1 * 6 * 4 * 4)^{\frac{1}{12}}, (1 * 4 * 5 * 3 * 4 * 4 * 2 * 3 * 2 * 7 * 5* \\ 5)^{\frac{1}{12}}, (1 * 5 * 6 * 4 * 5 * 5 * 3 * 4 * 3 * 8 * 6 * 6)^{\frac{1}{12}} = (2 \cdot 4, 3 \cdot 35, 4.21). \tag{14}$$

Appendix G also displays the final values for the fuzzy geometric means in a similar way.

Next, for each criterion, fuzzy weights need to be created. To calculate fuzzy weights, equation (15) is utilized.

$$W = r_1 (r_1 * r_2 ....r_n)-^{1} \tag{15}$$

First, all values of the fuzzy geometric mean must be added. Equation (16) for adding fuzzy geometric values is provided below:

$$1 + A2 = (l1, m1, u1) + (l2, m2, u2) = (l1 + l2, m1 + m2, u1 + u2) \tag{16}$$

The lower, middle, and upper values are added to generate the total of fuzzy number:

$$(r_1 + r_2 + r_3 + r_4 + r_5 + r_6 + r_7 + r_8 + r_9 + r_{10} + r_{11} + r_{12}) = (2.4 + 1.5 + 1.5 + 1.1+ \\ 1.1 + 0.9 + 0.7 + 0.6 + 0.4 + 0.3 + 0.2 + 0.2, 3.35 + 2.24 + 2.03 + 1.55 + 1.43 + 1.26+ \\ 1.08 + 0.79 + 0.68 + 0.44 + 0.3 + 0.3, 4.21 + 2.96 + 2.63 + 2.02 + 1.94 + 1.87 + 1.69+ \\ 1.14 + 0.98 + 0.56 + 0.40 + 0.41) = (11.0, 15.47, 20.81) \tag{17}$$

The estimated values (11.0, 15.47, and 20.81) above need to be reciprocal, as shown by Equation (18). Using reciprocal Equation (17), the following calculation is performed and applied:

$$(r_1 + r_2 + r_3 + r_4 + r_5 + r_6 + r_7 + r_8 + r_9 + r_{10} + r_{11} + r_{12})^{-1} = \left(\frac{1}{11.0}, \frac{1}{15.47}, \frac{1}{20.81}\right) \tag{18}$$

The next step involves multiplying each fuzzy geometric mean value by the reciprocal of the geometric mean summation to the fuzzy weigh section. The next step, defuzzification, turns a fuzzy number into a precise numerical value. The defuzzification procedure is carried out as shown in Appendix F columns 9 (Fuzzy weight section) and Equation (19).

$$\text{Center of the area (Avarage)} = \left(\frac{(l + m + u)}{3}\right) \tag{19}$$

After weights have been obtained, they must all be added together, as shown in Appendix F. The calculated value of the sum is 1. However, it is suggested to normalize the weights. For every thematic layer in the study, the normalized weights were applied, adding up to 1. With an average weight of 21%, elevation had the most influence in the current study. followed by rainfall, LULC lineament density, and soil, with a weight of 14, 13, 10, and 10% respectively. However, it was determined that curvature, TPI, NDVI, and TWI had the least influence on finding GWPZs with a weight of 2, 2, 3, and 4%. This indicates that these parameters have comparatively less impact while weighed against other variables. To create the final GWPZ map, the thematic layers indicating the influential elements were layered using ArcGIS's weighted overlay analysis. Figure 3 illustrates the resulting map, displaying the GWPZs in the study area. Additionally, four zones – low, moderate, high, and very high – were added to this map to indicate different levels of groundwater potential.

3. Result and discussion

During dry seasons, there is usually a shortage of water for irrigation in farming and for domestic use, and on the other hand, there is flooding that leads to erosion and huge losses in agriculture during the rainy seasons or monsoon season. To address the groundwater challenges in the Markanda Watershed such as seasonal water scarcity, flooding, and over-extraction a comprehensive management strategy is essential. This includes implementing rainwater harvesting and artificial recharge structures like check dams, percolation tanks, and recharge wells to capture monsoon rainfall and replenish aquifers.

Flood management can be enhanced by constructing levees, embankments, and controlled drainage systems that direct excess water into recharge zones, reducing soil erosion and promoting groundwater recharge. Promoting sustainable agricultural practices, such as drip and sprinkler irrigation, crop rotation, and drought-resistant crops, can help reduce water demand and enhance soil moisture retention. Community-based initiatives, including water user associations, can empower local stakeholders to monitor groundwater levels, regulate extraction, and implement conservation measures. Additionally, enforcing groundwater regulation policies and a permitting system for large-scale extraction will prevent overuse, while promoting conjunctive use of surface and groundwater resources can optimize water availability throughout the year. Mitigating these hydrological issues will be pivotal to realizing sustainable water resources and safe agricultural production in the region [63]. These strategies, supported by advanced GIS, remote sensing, AHP, and Fuzzy-AHP models, provide a robust framework for sustainable groundwater management, ensuring water security, reducing flooding risks, and supporting agricultural productivity in the region.

3.1 GWPZ identification by AHP

In our study, 2.45% (0.8821 km^2) of the study area was classed as "Very High," with 52.92% (19.0523 km^2), classified as "High", similarly moderate GWPZ as 16.0532 km^2 (44.59%), and low is 0.0124 km^2 (0.034%), respectively. Using AHP weighted and pairwise calculations, the classed raster data were utilized in the GIS analysis to find potential zones for groundwater (Figure 5). The primary judgmental indication used to relate to the AHP computation was the CR. The site selection procedure's important factor was calculated and it was found a CR of 0.096 in the current results (Table 2). To find the best location for groundwater, this study uses the analytic hierarchy approach to generate the weighted values of the chosen criterion and weighted overlay analysis to assess the generated rating of the sub-criteria. The site's suitability map was created by combining the chosen criteria with weighted overlay tools and AHP weights. According to a study, in research conducted in the Barind tract in the northwestern part of Bangladesh, 4% of the study area was classed as "very high" and 13% as "high" GPWZs [64], while the study discovered that 19.34% of a study area in Dak Nong Province, Vietnam, has "high" groundwater potential [65]. According to the research, a study conducted in Ethiopia's Beles River Basin revealed that roughly 19% of the region has "good" groundwater potential [66]. Furthermore, the study discovered that between 6% to 18% of the area is designated as "very high" or "high" GWP zones [67].

Table 2: *Details area and percentage of AHP and F-AHP methods for GWPZ identification.*

Groundwater Potential Zones	Areas (km^2)	Area (%)	Areas (km^2)	Area (%)
Very High	0.8821	2.450278	2.5334	7.0372222
High Potential	19.0523	52.92306	15.2127	42.2575
Moderate Potential	16.0532	44.59222	13.3812	37.17
Low	0.0124	0.034444	4.8727	13.535278

India makes up over 2.4% of the world's land area and is home to almost 18% of its population. India uses 4% of the world's water supply. According to World Bank research, India is the country

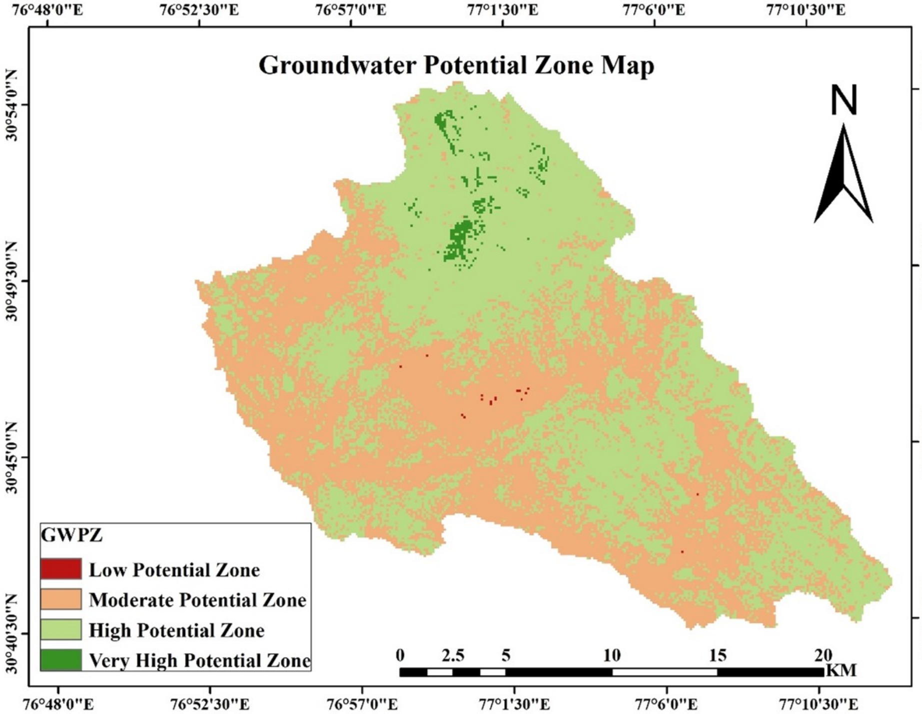

Figure 5: *AHP-based GWPZ Map in the study area.*

that uses groundwater the most. The usage of groundwater is anticipated to increase further as India's economy and population expand. It has increased the demand on India's groundwater supplies [1]. In both rural and urban parts of India, groundwater is essential to agriculture and the security of drinking water. An essential component of India's water security is groundwater. Experts contend that India's groundwater administration has several shortcomings that impede conservation efforts. To solve India's declining groundwater levels, groundwater governance changes and the encouragement of prudent groundwater usage are needed [68]. According to the Central Groundwater Board of India, around 17% of groundwater blocks are overexploited, meaning that the rate of extraction is higher than the rate at which the aquifer recharges, while 5% and 14% of blocks are in critical and semi-critical phases, respectively. The North-western, Western, and Southern peninsular regions are the three main areas where the situation is very concerning. In comparison with 2017, the number of "overexploited" groundwater units has decreased by 3%, while the number of "safe" category units has increased by 4%, according to the Groundwater Resource Assessment (2022). In 909 units, the groundwater conditions improved [69].

3.2 GWPZ identification by Fuzzy-AHP

Potential groundwater zones were identified by the GIS study utilizing fuzzy AHP weighted and paired computations on the categorized raster data (Figure 6). As per the analysis, GWPZ is very high 2.5334 km^2 (7.037%), high 15.2127 km^2 (42.2575%), moderate 13.3812 km^2 (37.17%), and the low potential zone is 4.8727 km^2 (13.535%), respectively. Prior research has demonstrated that by taking into consideration the variation in decision-making criteria, fuzzy AHP may improve the accuracy of GWPZs delineation [61]. The results of the current study, which have an Area

Under the Curve (AUC) value of 0.763, support these conclusions and indicate that the Markanda Watershed's ideal groundwater locations can be reliably predicted (Table 2). When uncertainties are not explicitly taken into consideration, the standard AHP technique usually produces lower accuracy rates; in contrast, this AUC result shows a rather high degree of model performance. The site suitability map's resilience is further increased by using the Normalizing Weight technique to generate weighted values for the chosen criterion and assess sub-criteria ratings. The chosen criteria were blended with weighted values and fuzzy AHP weights to create the site's suitability map.

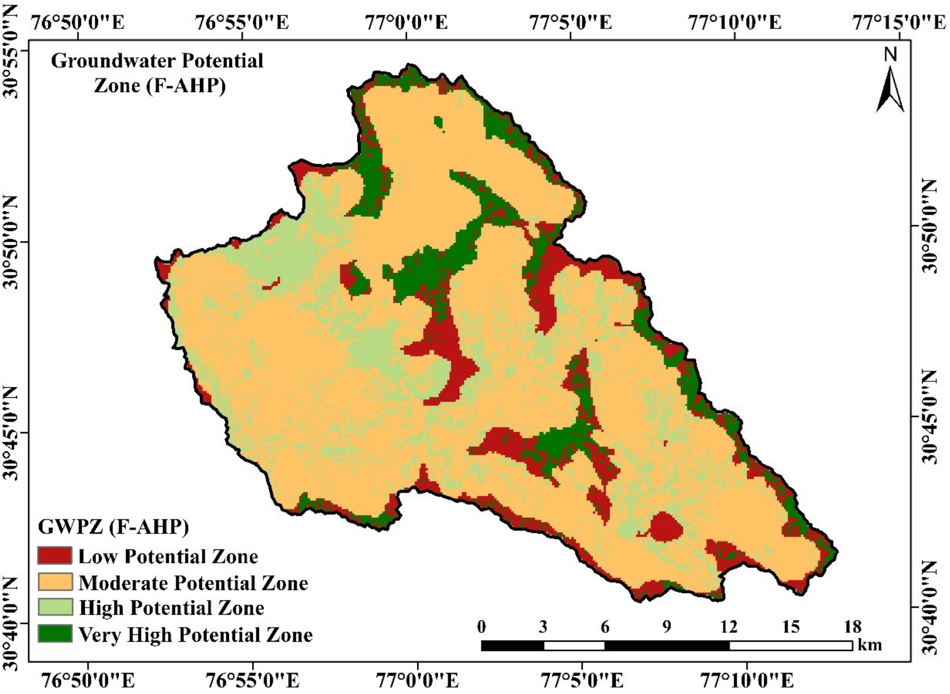

Figure 6: *Fuzzy AHP-based GWPZ Map in the study area.*

Since India uses more groundwater than any other nation in the world, the condition of its groundwater is a serious problem. In India, around 437.60 billion cubic meters of groundwater are recharged yearly, compared to 239.16 billion cubic meters that are withdrawn. Over-extraction is one of the main challenges. From 2004 to 2017, groundwater extraction surpassed the recharge rate, rising from 58% to 63% [28]. Contamination: The main cause of groundwater pollution is geogenic contamination, which is a serious problem. Climate Change: Discontinuous droughts and sporadic rains are examples of climate shocks decreasing groundwater recharge. Unplanned Urbanization: resulting in urbanization, groundwater recharge is decreased and pollution rises. Different locations have different groundwater availability. For example, the northern regions especially Punjab, Haryana, Delhi, and western Uttar Pradesh face critical groundwater levels. Improved groundwater management initiatives include the Model Groundwater Bill, which promotes sustainable groundwater management practices, the Jal Jeevan Mission, which aims to supply all rural households with safe drinking water by 2024, the National Project on Aquifer Management, which maps and manages aquifers, and the Atal Bhujal Yojana, which promotes participatory groundwater management. Resolving India's groundwater issues, in general, calls for a multifaceted strategy that includes sustainable management techniques, community involvement, and regulatory changes [70].

3.3 Validation

The GIS-based AHP and fuzzy-AHP methods were combined with overlay investigations of the chosen parameters mentioned above to create the GWPZ map of the research region. The ROC is a widely used method for evaluating the accuracy of a model result [71]. The accuracy of the model is shown by the AUC in ROC analysis. Based on the qualitative and quantitative relationships between the AUC value and prediction accuracy, the correlation can be categorized into five groups. Excellent (0.9–1), very good (0.8–0.9), good (0.7–0.8), average (0.6–0.7), and bad (0.5–0.6) are these classifications [72]. According to the study's findings, the AHP model has an AUC value of 0.714, which is comparatively less accurate than the other model. The AUC of the GWPZ map using AHP was 0.714, indicating a 71.4% accuracy rate for the model (Figure 7 - 8). Conversely, the GWPZ map using Fuzzy-AHP demonstrated an AUC of 0.763, indicating a 76.3% accuracy rate for the model (Figure 7). The accuracy of the model indicates that the findings of AHP and Fuzzy-AHP are both good. However, the evaluation of groundwater potential is better performed by Fuzzy-AHP.

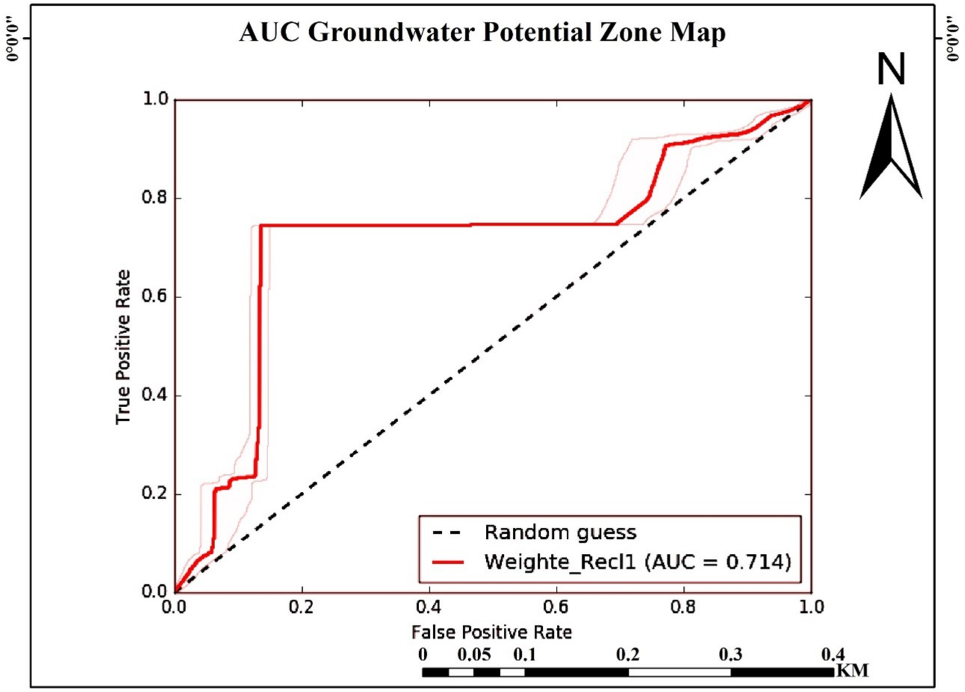

Figure 7: *AUC information of AHP P for GWPZ identification.*

The country's largest river system is the Ganges basin system, which spans around 86.1 million hectares [73]. A regional alluvial aquifer system, considered to be among the world's most productive, is formed by the Indus–Ganges–Brahmaputra (IGB) systems, which collectively drain the northern Indian plains. In contrast, the remaining two-thirds of the nation has restricted groundwater availability in the weathered zone and beneath fractured aquifers. Pre-Cenozoic crystalline rocks, consolidated sedimentary formations, and multi-layered basalt flows of the Indian craton make up the majority of fractured aquifers, whereas the porous and permeable aquifers in the north are both unconsolidated and semi-unconsolidated alluvial sedimentary types [74]. In the most populated region of the nation, the extremely fertile IGB basin, intense irrigation is common. In 2011, the annual groundwater draw was around 245 bcm, while the projected renewable groundwater resources were 433 bcm. Approximately 223 bcm of groundwater was utilized for irrigation, with the remaining

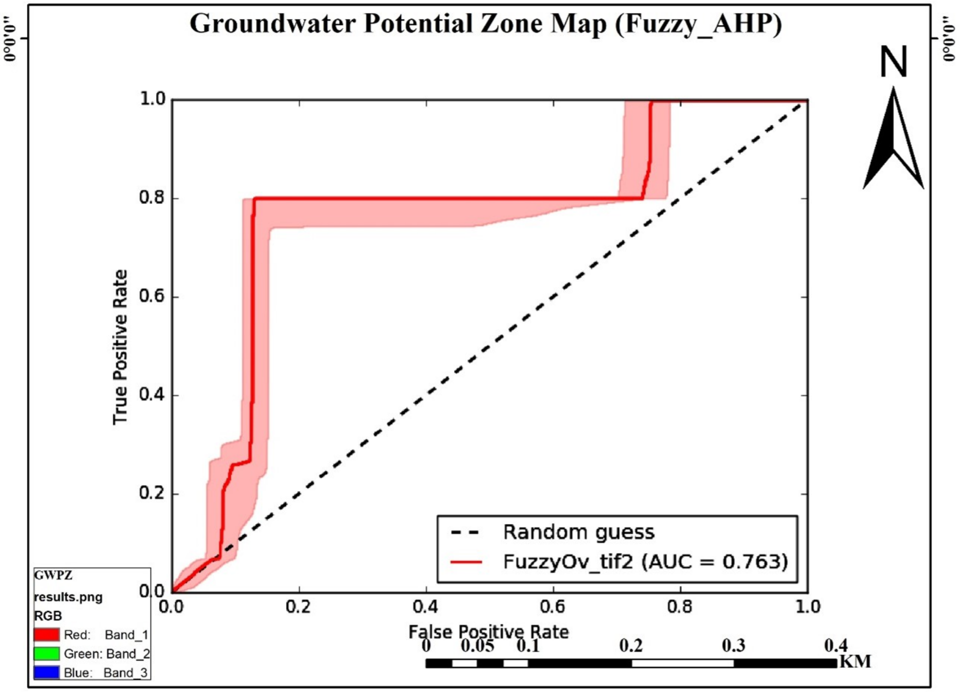

Figure 8: *AUC information of F-AHP for GWPZ identification.*

23 bcm being utilized for residential and commercial uses [75]. Between the 1950s and 2000, crop output quadrupled (from 50 to 204 million tons) due to expanding agricultural demand for a growing population, further taxing groundwater supplies [76]. Rapid groundwater storage loss has been noted in the ISC's mostly farmed areas [77]. There has been a more than 4 m drop in groundwater levels compared to the decadal norm in several regions of the nation. Furthermore, groundwater in a significant portion of the shallow alluvial aquifers in northern India is anoxic and enriched with increased As concentrations, much like its eastern neighbor Bangladesh [78]. The groundwaters of 86 districts across 10 Indian states have been found to have elevated amounts (https://cgwb.gov.in/). It is thought that widespread groundwater abstraction has made the contamination much worse [79]. In portions of 19 states, high levels of groundwater fluoride have also been found, primarily in the crystalline aquifers [80]. Additionally, elevated levels of nitrate (NO3-) and groundwater iron (Fe) have been observed in several aquifers around the nation (https://cgwb.gov.in/). Though very brackish groundwater is also common in the interior aquifers of various states, seawater intrusion has been reported in many of the coastal aquifers that border the Arabian Sea and the Bay of Bengal, causing aquifer salinization (https://cgwb.gov.in/). Mineral dissolution and/or agricultural contamination may be connected to this type of inland salinization. In regions of eastern India, extreme precipitation and reclaimed recharge often result in widespread floods.

4. Limitation and future research direction

Several limits need to be acknowledged in this study. The methods of AHP and Fuzzy AHP also contain a problem with subjectivity in assigning weights to factors while using it, which brings in bias. However, it should be noted that the outcomes of the study are related only to the Markanda Watershed and may not be relevant in other parts of the world with different conditions. Lastly, the model is static and it does not include any interactions in these changing climatic conditions, land use, and water demand that may have impacts on the availability of groundwater. In the future, studies could examine how to apply innovative modeling methods, such as weight of evidence, artificial neural networks, and machine learning algorithms, to increase the precision of groundwater potential mapping. In addition, future research can concentrate on examining the groundwater potential's temporal fluctuation in the Markanda watershed utilizing isotopic analysis results along with historical data and trends. Future researchers can also concentrate on investigating the relationships between surface and groundwater, enhancing data integration, adding socioeconomic variables, taking climate change effects into account, and putting long-term models and monitoring into practice. Developing successful groundwater management techniques will benefit greatly from an understanding of the dynamics of groundwater potential throughout time.

5. Conclusion

The present study aims to define GWPZs in the Markenda Watershed in India by combining AHP, and Fuzzy-AHP approaches with integrated data, including remote sensing and GIS. Rainfall, soil, slope drainage density, lineament density, elevation, LULC, aspect, NDVI, TWI, TPI, and curvature were the 12 thematic layers used in this study and were analyzed to define the GWPZs. As seen in the final GWPZ map, the current research region was divided into four distinct sections, each with a different level of groundwater potential. Among the factors considered, elevation significantly influenced groundwater potential in the models (AHP, Fuzzy-AHP, and TOPSIS). The results of ROC calculations used to evaluate predictive capability showed that the AHP technique (AUC ¼ 71.4%) was less precise than the Fuzzy-AHP strategy (AUC ¼ 76.3%). The Fuzzy-AHP technique's GWPZ map is useful for groundwater management and planning in the study's area. Based on the study's findings, a targeted groundwater management plan is proposed to optimize resource use and sustainability. High-potential zones should be prioritized for groundwater extraction and recharge projects, incorporating measures like check dams, percolation tanks, and efficient irrigation practices. Moderate-potential areas require a balanced approach, involving controlled groundwater pumping, artificial recharge, and rainwater harvesting to maintain aquifer levels. Low-potential zones should focus on reducing groundwater dependence and enhancing surface water storage to prevent overexploitation. Decision-makers may utilize the research findings to create sensible development plans and efficient groundwater management methods to preserve sustainable groundwater use in the region. To ensure the best possible use of groundwater resources in Markanda Watershed, decisions can be made by taking into consideration the integrated strategy and methodology used in this study. Future research on GWPZs may concentrate on investigating the relationships between surface and groundwater, enhancing data integration, adding socioeconomic variables, taking climate change effects into account, and putting long-term monitoring and modeling into practice.

Conflict of interest: The authors declare no conflict of interest to any party.

Abbreviation

AHP Analytic Hierarchy Process
AUC Area Under the Curve
BWoE Bayesian Weights of Evidence
DD Drainage Density
FR Frequency Ratio
GIS Geographic Information System
GWPZ Groundwater Potential Zone
LD Lineament Density
LULC Land Use Land Cover
NDVI Normalized Difference Vegetation Index
RS Remote Sensing
ROC Receiver Operating Characteristics

SD Spring Density
TWI Topographic Witness Index
TOPSIS Technique for Order of Preference by Similarity to Ideal Solution
WoE Weights of Evidence

References

[1] S. Roy, A. Bose, and G. Mandal, "Modeling and mapping geospatial distribution of groundwater potential zones in Darjeeling Himalayan region of India using analytical hierarchy process and GIS technique," Model. Earth Syst. Environ., vol. 8, no. 2, pp. 1563–1584, 2022.

[2] N. P. Zade, A. Bhosale, P. K. Dhir, P. Sarkar, and R. Davis, "Variability of Mechanical Properties of Cellular Lightweight Concrete Infill and Its Effect on Seismic Safety," Nat. Hazards Rev., vol. 22, no. 4, 2021, doi: 10.1061/(asce)nh.1527-6996.0000501.

[3] S. Das, "Comparison among influencing factor, frequency ratio, and analytical hierarchy process techniques for groundwater potential zonation in Vaitarna basin, Maharashtra, India," Groundw. Sustain. Dev., vol. 8, pp. 617–629, 2019, doi: 10.1016/j.gsd.2019.03.003.

[4] B. Halder, J. Bandyopadhyay, and S. Hemram, "Groundwater harvesting and artificial recharge site identification on upper Shilabati watershed using geospatial approaches," Theor. Appl. Climatol., pp. 1–26, 2024.

[5] T. Goswami and S. Ghosal, "Understanding the suitability of two MCDM techniques in mapping the groundwater potential zones of semi-arid Bankura District in eastern India," Groundw. Sustain. Dev., vol. 17, p. 100727, 2022, doi: 10.1016/j.gsd.2022.100727.

[6] R. Nyakundi, M. Nyadawa, and J. Mwangi, "Effect of Recharge and Abstraction on Groundwater Levels," Civ. Eng. J., vol. 8, no. 5, pp. 910–925, 2022, doi: 10.28991/cej-2022-08-05-05.

[7] S. V. R. Termeh et al., "Optimization of an adaptive neuro-fuzzy inference system for groundwater potential mapping," Hydrogeol. J., vol. 27, no. 7, pp. 2511–2534, 2019, doi: 10.1007/s10040-019-02017-9.

[8] F. Mumtaz et al., "Impacts of Green Fraction Changes on Surface Temperature and Carbon Emissions: Comparison under Forestation and Urbanization Reshaping Scenarios," Remote Sens., vol. 15, no. 3, p. 859, 2023, doi: 10.3390/rs15030859.

[9] S. R. Naganna, B. H. Beyaztas, N. Bokde, and A. M. Armanuos, "ON THE EVALUATION OF THE GRADIENT TREE BOOSTING MODEL FOR GROUNDWATER LEVEL FORECASTING," Knowledge-Based Eng. Sci., vol. 1, no. 1, pp. 48–57, 2020.

[10] R. Connor, The United Nations world water development report 2015: water for a sustainable world, vol. 1. UNESCO publishing, 2015.

[11] U. Das, S. Chaudhuri, B. Halder, and P. Dutta, "An Overview of the Groundwater Situation in Namkhana Block, Sundarban Biosphere Reserve, India, from the Pinnacle of a Propagating Delta Front: A Post-Monsoonal Survey.," J. Water Manag. Model., 2024.

[12] H. Tao et al., "Groundwater level prediction using machine learning models: A comprehensive review," Neurocomputing, vol. 489, pp. 271–308, 2022.

[13] M. F. U. Moazzam, G. Rahman, S. Munawar, A. Tariq, Q. Safdar, and B.-G. Lee, "Trends of Rainfall Variability and Drought Monitoring Using Standardized Precipitation Index in a Scarcely Gauged Basin of Northern Pakistan," Water, vol. 14, no. 7, p. 1132, 2022, doi: 10.3390/w14071132.

[14] A. Armanuos, K. Ahmed, M. Sanusi Shiru, and M. Jamei, "Impact of Increasing Pumping Discharge on Groundwater Level in the Nile Delta Aquifer, Egypt," Knowledge-Based Eng. Sci., vol. 2, no. 2, pp. 13–23, 2021, doi: 10.51526/kbes.2021.2.2.13-23.

[15] M. Israil, M. Al-hadithi, and D. C. Singhal, "Application of a resistivity survey and geographical information system (GIS) analysis for hydrogeological zoning of a piedmont area, Himalayan foothill region, India," Hydrogeol. J., vol. 14, no. 5, pp. 753–759, 2005, doi:

10.1007/s10040-005-0483-0.

[16] K. El Hairchi et al., “Groundwater potential zones Modeling using GIS, remote sensing, and AHP Method in the Guigou basin, Morocco.” Research Square Platform LLC, 2023. doi: 10.21203/rs.3.rs-2989666/v1.

[17] M. Sathiyamoorthy et al., “Sustainability of Groundwater Potential Zones in Coastal Areas of Cuddalore District, Tamil Nadu, South India Using Integrated Approach of Remote Sensing, GIS and AHP Techniques,” Sustainability, vol. 15, no. 6, p. 5339, 2023, doi: 10.3390/su15065339.

[18] A. A. J. Ghanim, A. M. Al-Areeq, M. Benaafi, M. S. Al-Suwaiyan, A. A. Al Aghbari, and M. Alyami, “Mapping Groundwater Potential Zones in the Habawnah Basin of Southern Saudi Arabia: An AHP- and GIS-based Approach,” Sustainability, vol. 15, no. 13, p. 10075, 2023, doi: 10.3390/su151310075.

[19] A. Farahmand, M. S. Hussaini, H. A. Jawadi, M. Abrunhosa, and B. F. Thomas, “Multi-criteria decision process to identify groundwater potential zones using geospatial tools in the Arghandab river basin, Afghanistan,” Environ. Earth Sci., vol. 82, no. 14, 2023, doi: 10.1007/s12665-023-11046-3.

[20] Z. Shao, M. E. Huq, B. Cai, O. Altan, and Y. Li, “Integrated remote sensing and GIS approach using Fuzzy-AHP to delineate and identify groundwater potential zones in semi-arid Shanxi Province, China,” Environ. Model. amp; Softw., vol. 134, p. 104868, 2020, doi: 10.1016/j.envsoft.2020.104868.

[21] T. Kuo, “A modified TOPSIS with a different ranking index,” Eur. J. Oper. Res., vol. 260, no. 1, pp. 152–160, 2017, doi: 10.1016/j.ejor.2016.11.052.

[22] V. Aslan, “Evaluation of Sanliurfa Karakopru basin groundwater potential for sustainability with GIS-based AHP and TOPSIS methods,” Sustain. Water Resour. Manag., vol. 9, no. 3, 2023, doi: 10.1007/s40899-023-00844-z.

[23] F. Islam et al., “Comparative analysis of GIS and RS based models for delineation of groundwater potential zone mapping,” Geomatics, Nat. Hazards Risk, vol. 14, no. 1, 2023, doi: 10.1080/19475705.2023.2216852.

[24] J. Wang and Q. Chen, “Strategic Decision Making: Applying the Analytic Hierarchy Process,” Interfaces (Providence)., 2005.

[25] P. J. M. van Laarhoven and W. Pedrycz, “A fuzzy extension of Saaty’s priority theory,” Fuzzy Sets Syst., 1983, doi: 10.1016/S0165-0114(83)80082-7.

[26] E. Şener, Ş. Şener, and A. Davraz, “Groundwater potential mapping by combining fuzzy-analytic hierarchy process and GIS in Beyşehir Lake Basin, Turkey,” Arab. J. Geosci., 2018, doi: 10.1007/s12517-018-3510-x.

[27] R. Thapa, S. Gupta, S. Guin, and H. Kaur, “Assessment of groundwater potential zones using multi-influencing factor (MIF) and GIS: a case study from Birbhum district, West Bengal,” Appl. Water Sci., vol. 7, no. 7, pp. 4117–4131, 2017, doi: 10.1007/s13201-017-0571-z.

[28] K. P. Dandge and S. S. Patil, “Spatial distribution of ground water quality index using remote sensing and GIS techniques,” Appl. Water Sci., vol. 12, no. 1, p. 7, Jan. 2022, doi: 10.1007/s13201-021-01546-7.

[29] A. P. dos Santos et al., “The Influence of Land Use and Land Cover on Surface Temperature in a Water Catchment Sub-Basin,” Soc. Nat., vol. 35, pp. e69161–e69161, 2023, doi: 10.14393/sn-v35-2023-69161.

[30] O. Singh and D. Kumar, “Evaluating the influence of watershed characteristics on flood vulnerability of Markanda River basin in north-west India,” Nat. Hazards, vol. 96, no. 1, pp. 247–268, 2018, doi: 10.1007/s11069-018-3540-4.

[31] D. Tien Bui et al., “A Hybrid Computational Intelligence Approach to Groundwater Spring Potential Mapping,” Water, vol. 11, no. 10, p. 2013, 2019, doi: 10.3390/w11102013.

[32] J. Saade, M. Atieh, S. Ghanimeh, and G. Golmohammadi, “Modeling Impact of Climate

Change on Surface Water Availability Using SWAT Model in a Semi-Arid Basin: Case of El Kalb River, Lebanon," Hydrology, vol. 8, no. 3, p. 134, 2021, doi: 10.3390/hydrology8030134.
[33] A. Tariq et al., "Integrated use of Sentinel-1 and Sentinel-2 data and open-source machine learning algorithms for burnt and unburnt scars," Geomatics, Nat. Hazards Risk, vol. 14, no. 1, 2023, doi: 10.1080/19475705.2023.2190856.
[34] G. N. Delin, R. W. Healy, M. K. Landon, and J. K. Böhlke, "EFFECTS OF TOPOGRAPHY AND SOIL PROPERTIES ON RECHARGE AT TWO SITES IN AN AGRICULTURAL FIELD1," JAWRA J. Am. Water Resour. Assoc., vol. 36, no. 6, pp. 1401–1416, 2000, doi: 10.1111/j.1752-1688.2000.tb05735.x.
[35] E. Kamali Maskooni, S. A. Naghibi, H. Hashemi, and R. Berndtsson, "Application of Advanced Machine Learning Algorithms to Assess Groundwater Potential Using Remote Sensing-Derived Data," Remote Sens., vol. 12, no. 17, p. 2742, 2020, doi: 10.3390/rs12172742.
[36] A. N. STRAHLER, "HYPSOMETRIC (AREA-ALTITUDE) ANALYSIS OF EROSIONAL TOPOGRAPHY," Geol. Soc. Am. Bull., vol. 63, no. 11, p. 1117, 1952, doi: 10.1130/0016-7606(1952)63[1117:haaoet]2.0.co;2.
[37] "Drainage-basin characteristics," Eos, Trans. Am. Geophys. Union, vol. 13, no. 1, pp. 350–361, 1932, doi: 10.1029/tr013i001p00350.
[38] P. R. Shekar and A. Mathew, "Delineation of groundwater potential zones and identification of artificial recharge sites in the Kinnerasani Watershed, India, using remote sensing-GIS, AHP, and Fuzzy-AHP techniques," AQUA — Water Infrastructure, Ecosyst. Soc., vol. 72, no. 8, pp. 1474–1498, 2023, doi: 10.2166/aqua.2023.052.
[39] B. Guru, K. Seshan, and S. Bera, "Frequency ratio model for groundwater potential mapping and its sustainable management in cold desert, India," J. King Saud Univ. - Sci., vol. 29, no. 3, pp. 333–347, 2017, doi: 10.1016/j.jksus.2016.08.003.
[40] IHEE, "ETUDE D'IMPACT sur L'ENVIRONNEMENT (EIE) DU PROJET de REALISATION de la STATION de DESSALEMENT D'EAU de MER a DJERBA (Rapport Définitif)," 2015. [Online]. Available: https://www.scribd.com/document/503047492/EIE-Dessalement-Djerba
[41] B. J. Ritzel, J. W. Eheart, and S. Ranjithan, "problem Potential Well Site Hypothetical Contaminant," Water Resour. Res., vol. 30, no. 5, pp. 1589–1603, 1994.
[42] N. Subba Rao, "A numerical scheme for groundwater development in a watershed basin of basement terrain: a case study from India," Hydrogeol. J., vol. 17, no. 2, pp. 379–396, 2008, doi: 10.1007/s10040-008-0402-2.
[43] H.-L. Yu and Y.-C. Lin, "Analysis of space–time non-stationary patterns of rainfall–groundwater interactions by integrating empirical orthogonal function and cross wavelet transform methods," J. Hydrol., vol. 525, pp. 585–597, 2015, doi: 10.1016/j.jhydrol.2015.03.057.
[44] S. Karimi-Rizvandi et al., "Groundwater-Potential Mapping Using a Self-Learning Bayesian Network Model: A Comparison among Metaheuristic Algorithms," Water, vol. 13, no. 5, p. 658, 2021, doi: 10.3390/w13050658.
[45] B. T. Pham, A. Jaafari, I. Prakash, S. K. Singh, N. K. Quoc, and D. T. Bui, "Hybrid computational intelligence models for groundwater potential mapping," CATENA, vol. 182, p. 104101, 2019, doi: 10.1016/j.catena.2019.104101.
[46] S. Solomon and F. Quiel, "Groundwater study using remote sensing and geographic information systems (GIS) in the central highlands of Eritrea," Hydrogeol. J., vol. 14, no. 6, pp. 1029–1041, 2006, doi: 10.1007/s10040-006-0096-2.
[47] Y. Hong and M. Abdelkareem, "Integration of remote sensing and a GIS-based method for revealing prone areas to flood hazards and predicting optimum areas of groundwater resources," Arab. J. Geosci., vol. 15, no. 1, 2022, doi: 10.1007/s12517-021-09422-z.
[48] E. Morin et al., "Flood routing and alluvial aquifer recharge along the ephemeral arid Kuiseb

River, Namibia," J. Hydrol., vol. 368, no. 1–4, pp. 262–275, 2009, doi: 10.1016/j.jhydrol.2009.02.015.
[49] C. Serele, A. Pérez-Hoyos, and F. Kayitakire, "Mapping of groundwater potential zones in the drought-prone areas of south Madagascar using geospatial techniques," Geosci. Front., vol. 11, no. 4, pp. 1403–1413, 2020, doi: 10.1016/j.gsf.2019.11.012.
[50] M. A. Al-Shalabi, S. Bin Mansor, N. Bin Ahmed, and R. Shiriff, "GIS based multicriteria approaches to housing site suitability assessment," in XXIII FIG congress, shaping the change, Munich, Germany, October, 2006, pp. 8–13.
[51] G. A. Kiker, T. S. Bridges, A. Varghese, T. P. Seager, and I. Linkov, "Application of multicriteria decision analysis in environmental decision making," Integr. Environ. Assess. Manag., vol. 1, no. 2, pp. 95–108, 2005, doi: 10.1897/ieam 2004a-015.1.
[52] W. Miller, M. G. Collins, F. R. Steiner, and E. Cook, "An approach for greenway suitability analysis," Landsc. Urban Plan., vol. 42, no. 2–4, pp. 91–105, 1998, doi: 10.1016/s0169-2046(98)00080-2.
[53] B. Feizizadeh, P. Jankowski, and T. Blaschke, "A GIS based spatially-explicit sensitivity and uncertainty analysis approach for multi-criteria decision analysis," Comput. Geosci., vol. 64, pp. 81–95, 2014, doi: 10.1016/j.cageo.2013.11.009.
[54] T. L. Saaty, "How to make a decision: The analytic hierarchy process," Eur. J. Oper. Res., vol. 48, no. 1, pp. 9–26, 1990, doi: 10.1016/0377-2217(90)90057-i.
[55] T. L. Saaty, "The Analytic Network Process – Dependence and Feedback in Decision-Making," Business Applications and Computational Intelligence. IGI Global, pp. 360–387, 2006. doi: 10.4018/978-1-59140-702-7.ch018.
[56] T. L. Saaty, Theory and applications of the analytic network process: decision making with benefits, opportunities, costs, and risks. RWS publications, 2005.
[57] S. K. Lee, G. Mogi, and K. S. Hui, "A fuzzy analytic hierarchy process (AHP)/data envelopment analysis (DEA) hybrid model for efficiently allocating energy R D resources: In the case of energy technologies against high oil prices," Renew. Sustain. Energy Rev., vol. 21, pp. 347–355, 2013.
[58] C. Kahraman, U. Cebeci, and D. Ruan, "Multi-attribute comparison of catering service companies using fuzzy AHP: The case of Turkey," Int. J. Prod. Econ., vol. 87, no. 2, pp. 171–184, 2004.
[59] R. R. Tan, K. B. Aviso, A. P. Huelgas, and M. A. B. Promentilla, "Fuzzy AHP approach to selection problems in process engineering involving quantitative and qualitative aspects," Process Saf. Environ. Prot., vol. 92, no. 5, pp. 467–475, 2014.
[60] C. G. E. Boender, J. G. de Graan, and F. A. Lootsma, "Multi-criteria decision analysis with fuzzy pairwise comparisons," Fuzzy Sets Syst., vol. 29, no. 2, pp. 133–143, 1989, doi: 10.1016/0165-0114(89)90187-5.
[61] T.-Y. Wang and Y.-H. Yang, "A fuzzy model for supplier selection in quantity discount environments," Expert Syst. Appl., vol. 36, no. 10, pp. 12179–12187, 2009.
[62] J. J. Buckley, "Fuzzy hierarchical analysis," Fuzzy Sets Syst., vol. 17, no. 3, pp. 233–247, 1985, doi: 10.1016/0165-0114(85)90090-9.
[63] J. A. Adesina, J. Jiang, and T. Xiaolan, "Integrated Watershed Management Framework and Groundwater Resources in Africa-A Review of West Africa Sub-region," 2021.
[64] R. M. Ferozur, C. S. Jahan, R. Arefin, and Q. H. Mazumder, "Groundwater potentiality study in drought prone barind tract, NW Bangladesh using remote sensing and GIS," Groundw. Sustain. Dev., vol. 8, pp. 205–215, 2019, doi: 10.1016/j.gsd.2018.11.006.
[65] D. H. Ha et al., "Quadratic Discriminant Analysis Based Ensemble Machine Learning Models for Groundwater Potential Modeling and Mapping," Water Resour. Manag., vol. 35, no. 13, pp. 4415–4433, 2021, doi: 10.1007/s11269-021-02957-6.
[66] I. Ahmad, M. A. Dar, T. G. Andualem, and A. H. Teka, "Groundwater development

using geographic information system," Appl. Geomatics, vol. 12, no. 1, pp. 73–82, 2019, doi: 10.1007/s12518-019-00283-6.

[67] M. Y. A. Khan, M. ElKashouty, A. M. Subyani, F. Tian, and W. Gusti, "GIS and RS intelligence in delineating the groundwater potential zones in Arid Regions: a case study of southern Aseer, southwestern Saudi Arabia," Appl. Water Sci., vol. 12, no. 1, 2021, doi: 10.1007/s13201-021-01535-w.

[68] D. Das, "Hydrogeochemical assessment of Groundwater in Sagar Island Region, South 24-Parganas, West Bengal, India," Int. J. Adv. Sci. Res. Manag., vol. 3, no. 11, 2018.

[69] CGWB, "Ground Water Resource Assessment," 2022.
[Online]. Available: https://cgwb.gov.in/en/ground-water-resource-assessment-0

[70] S. Barua, B. P. Mukhopadhyay, and A. Bera, "Hydrochemical assessment of groundwater for irrigation suitability in the alluvial aquifers of Dakshin Dinajpur district, West Bengal, India," Environ. Earth Sci., vol. 80, no. 16, 2021, doi: 10.1007/s12665-021-09832-y.

[71] S. Janizadeh et al., "Prediction success of machine learning methods for flash flood susceptibility mapping in the Tafresh watershed, Iran," Sustainability, vol. 11, no. 19, p. 5426, 2019.

[72] E. Yesilnacar and T. Topal, "Landslide susceptibility mapping: A comparison of logistic regression and neural networks methods in a medium scale study, Hendek region (Turkey)," Eng. Geol., vol. 79, no. 3–4, pp. 251–266, 2005, doi: 10.1016/j.enggeo.2005.02.002.

[73] C. W. Commission, "Water and related statistics," Water Resour. Inf. Syst. Dir. New Delhi, 2010.

[74] S. S. Yadav, L. Kumar, and A. Dey, "Groundwater year book 2014–2015: Rajasthan state," Reg. Off. Data Centre, Cent. Gr. Water Board-Western Reg. Jaipur, India, 2016.

[75] CGWB, "Dynamic Groundwater Resources, Meghalaya," 2022. [Online]. Available: https://www.cgwb.gov.in/old website/GW-Assessment/GWR-2022-Reports State/Meghalaya.pdf

[76] R. Kumar, R. D. Singh, and K. D. Sharma, "Water resources of India," Curr. Sci., pp. 794–811, 2005.

[77] S. N. Bhanja, A. Mukherjee, M. Rodell, I. Velicogna, K. Pangaluru, and J. S. Famiglietti, "Regional groundwater storage changes in the Indian subcontinent: the role of anthropogenic activities," in AGU Fall Meeting Abstracts, 2014, pp. GC21B-0533.

[78] P. Bhattacharya, A. Mukherjee, and A. B. Mukherjee, "Groundwater arsenic in India: source, distribution, effects and alternate safe drinking water sources," 2013.

[79] A. Mukherjee, A. E. Fryar, B. R. Scanlon, P. Bhattacharya, and A. Bhattacharya, "Elevated arsenic in deeper groundwater of the western Bengal basin, India: Extent and controls from regional to local scale," Appl. Geochemistry, vol. 26, no. 4, pp. 600–613, 2011.

[80] R. C. Maheshwari, "Fluoride in drinking water and its removal," J. Hazard. Mater., vol. 137, no. 1, pp. 456–463, 2006.