https://doi.org/10.52131/jee.2024.0502.0048

*i*RASD Journal of Energy & Environment

Volume 5, Number 2, 2024, Pages 111 - 130

Journal Homepage:
https://journals.internationalrasd.org/index.php/jee

*i*RASD JOURNAL OF ENERGY & ENVIRONMENT

INTERNATIONAL RESEARCH ASSOCIATION FOR SUSTAINABLE DEVELOPMENT

Modelling of Groundwater Potential Zones by using GIS and Remote Sensing Techniques: A Case Study of Multan District

Anila Anwar[1], Awais Munir[2], Noor Fatima[3], Asma Majeed[4], Hafiza Momina Rafiq[5], Iftikhar Ahmed[6]

[1] MS Scholar, Institute of Agro-Industry and Environment, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan. Email: anilaanwar277@gmail.com

[2] PhD Scholar, Department of Environmental Science, International Islamic University Islamabad, Pakistan. Lecturer at Institute of Agro-Industry and Environment, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan. Email: awais.munir@iub.edu.pk

[3] PhD Scholar, Centre of Excellence in Water Resource Engineering, University of Engineering and Technology, Lahore, Pakistan. Email: noorfatima0437@gmail.com

[4] Assistant Professor, Institute of Agro-Industry and Environment, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan. Email: asma.majeed@iub.edu.pk

[5] Student, Institute of Agro-Industry and Environment, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan. Email: hafizamominarafiq@gmail.com

[6] Assistant Professor at Department of Agricultural Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan. Email: iftikhar.ahmed@kfueit.edu.pk

ARTICLE INFO

Article History:

Received:	August	22, 2024
Revised:	December	24, 2024
Accepted:	December	25, 2024
Available Online:	December	26, 2024

Keywords:
Analytical Hierarchy Process (AHP)
Groundwater Potential
Physiographic Factors
Meteorological Impact
Weighted Overlay Analysis
GIS
Remote Sensing

JEL Classification Codes:
K32, P18, P46

Funding:
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

As groundwater plays a critical role in industry, residential as well as agricultural activities, its proper management is an important issue at the global level. In this paper, the Remote Sensing (RS), and Geographic Information System (GIS) technology are applied to forecasting the potential of ground water in Multan district of Pakistan. The level of water available in aquifers in various hydrological reasons is known as ground-water potential. To analyze the research area, there are eight significant factors that were considered and the research area is 3,721 square kilometers in size and is located in southern Punjab. They were drainage density, rainfall, soil texture, topographic wetness index (TWI), slope, aspect, elevation, and land cover and land use (LULC). The relative relevance of these aspects is determined by carrying out weighted overlay analysis with the Analytical Hierarchy Process (AHP) model. In the findings it is noted that there are four levels to the potentiality of ground water in the area of research; Low, moderate, high, and extremely high. The outcomes indicate that heavy vegetated areas experience low steepness of run off and high infiltration rates, which enhances recharging of groundwater. Rainfall and physiographic qualities mainly characterized by altitude and slope were identified as the most critical variables. Along with the provision of insightful information to be used in future planning and sustainable water resources management in the Multan District, this research provides evidence on the usefulness of GIS and RS technologies in evaluation of groundwater.

Corresponding Author's Email: awais.munir@iub.edu.pk

Citation: Anwar, A., Munir, A., Fatima, N., Majeed, A., Rafiq, H. M., & Ahmed, I. (2024). Modelling of Groundwater Potential Zones by using GIS and Remote Sensing Techniques: A Case Study of Multan District. *IRASD Journal of Energy & Environment*, *5*(2), 111–130. https://doi.org/10.52131/jee.2024.0502.0048

1. Introduction

An inseparable component of hydrological cycle as a key source of home consumption, industrial activities and farming across the globe, groundwater plays a vital role in the world. As known to be a very significant natural resource, ground water plays a critical role in jurisdictions with a low surface water supply to satisfy freshwater requirements and ensure economic activity (Al-Manmi & Rauf, 2016; Gang et al., 2024). Groundwater is vital to the agriculture-based economy of Pakistan and yet the over-exploitation, population, industrialization and poor methods of water management are becoming an increasing threat to ground-water. Overexploitation of groundwater reserves has aggravated the water problem of the nation, leading to the reduction of river and lake flow and the lowering of water quality, and water table (Moazzam et al., 2022). The ground water potential is the water stored in a given aquifer with the capacity of supporting various hydrological processes. The quantity of water placed in the subsurface may be over extracted to the extent that the level of water table is reduced (Guru et al., 2017). Moreover, such issues as loss of water quality and tables of lakes and streams decrease are getting even more problematic (Aneesh & Deka, 2015; Azizullah et al., 2011). In tackling the impacts of climate change on the groundwater supplies and the groundwater menace, proper monitoring is essential (Adiat et al., 2012; Hashemi et al., 2015).

To manage its water resources efficiently, especially in those regions that are arid and semi-arid such as southern Punjab, proper mapping of zones of ground water potential should therefore be done. Conventional methods of researching groundwater, like the geological and geophysical surveys may be very time consuming and labor intensive. To this end, remote sensing (RS) and geographic information systems (GIS) have proved to be powerful tools of mapping and assessing the variables that influence ground water recharge. Scientists can consider the environmental features in a more accurate way since the advantage of such technologies is spatial analysis of a large area (Al-Abadi & Al-Shamma'a, 2014; Manap et al., 2014).

Although GIS and RS have become the common tools, there is still the need to develop new integrated methods that may be applied to combine a variety of contributing factors systematically. This piece of work aims to fill this gap as it models groundwater potential zones in the Multan District based on the Analytical Hierarchy Process (AHP) coupled with GIS and RS. Because the search of potential zones of groundwater has been performed using multiple approaches, such as index-based and quantitative (Singh et al., 2018). AHP model could be regarded as the most well-known and widely applied Multi Criteria Decision Analysis (MCDA) technique in the determination of the zones of ground water prospecting (Al-Abadi, 2017). The paper provides comprehensive guide to understand the dynamics of groundwaters through evaluation and prioritization of factors namely; the drainage density, the land use and the land cover (LULC), the rainfall, soil texture, slope, topographic wetness index (TWI), aspect and elevation. Furthermore, AHP provides a rigor held and data-driven analysis that intact causal relationships and provides a quantitative assessment of the relative value of each parameter. The work that is done contributes to the growing body of knowledge on sustainable groundwater management and it contains useful information that can guide planners, law-makers, and local government officials. It answers a universal question regarding the pressing need to adopt effective groundwater conservation measures in the most water-scarce region in Pakistan by modulating innovative geospatial tools and a systematic complexity of decision making (Shahab et al., 2019). Ground water forms a form of water reservoir that is contained on the aquifers through the accumulation of water on the saturated regions below the ground. These aquifers are Mother Nature in such a way that they can contain the water in them over thousand years (Chowdhury et al., 2009; Murtaza et al., 2025). Geological formations, the texture of the soil, the density of drainage, and the precipitation pattern are some of the aspect that affects groundwater distribution and flow (Munir et al., 2025; Zhao et al., 2016). When it comes to freshwater requirements, the groundwater is required especially as the drinkable water (Al-Abadi & Al-Shamma'a, 2014; Al-Manmi & Rauf, 2016; Azizullah et al., 2011).

Inadequate irrigation practices, low level of underground water table also add to the salinity that reduces the ground water quality and limits their use. In salt-affected districts, geographical information system and remote sensing are vital in water sustainable management to determine ground water potential areas. Recognized as one of the most valuable natural resources, groundwater is taken as a primary source of clean and drinkable water throughout the climates of the world (Ahmed et al., 2022; Manap et al., 2014). Groundwater is a dynamic source of agricultural economy in Pakistan. This important natural resource, however, is extremely susceptible to the depletion caused by the high rate of population growth, rising industrial activity, uncontrolled use of groundwaters and its poor administration (Moazzam et al., 2022; Shahab et al., 2019).

Groundwater potential refers to the amount of water that is found in a well-defined area and which maintains different hydrological functions. Pakistan has the ground water as one of its main sources of irrigation. Climate change also impacts on the river water flows leading to a decrease in food security and the economy (Bashir et al., 2019; Khair et al., 2012). This is why the existing supplies of subsurface waters usable during irrigation are explored and divided into categories, and layouts of sheltering such deposits are being developed (Chang et al., 2017; Xiang et al., 2020). In finding the ground water potential areas under the local conditions many processes are adopted. The identification of an aquifer would be optimum due to the effective planning and management based on the exploitation of the geological, geophysical and hydrogeological features of an aquifer. Potentiality has also been considered to be a major factor in the development of water resources as well as accretion (Anbazhagan & Jothibasu, 2016; Manap et al., 2014).

The evaluation of the zones of ground water resources possibilities is carried out in accordance with a broad spectrum of methods used by the reactors worldwide, including a logistic regression (Pourghasemi & Beheshtirad, 2015), multi-criteria decision analysis (Chowdhury et al., 2009), frequency ratio (Ozdemir, 2011), weights of evidence (Lee et al., 2012), decision trees (Chenini & Ben Mammou, 2010), Shannon entropy (Naghibi et al., Traditionally, satellite based remote sensing (RS) /Geographic information system (GIS) is one of the new ways of learning about groundwater commercially. Due to recent practises, including GIS and RS, a number of geo-environmental features can be mapped and assessed better in comparison to the old practise methods (Al-Djazouli et al., 2021).

The remote sensing and geographic information systems could be the excellent means to gather, administer, and keep spatial data in an easy manner (Arivalagan, Kiruthika, et al., 2014; Khelifi, 2019; Mahalingam & Vinay, 2015; Pani et al., 2016). GIS is another of the methods that has held out the promise in researching the ground water. Remote sensing has been quite useful given the fact that it has benefits like spectral, spatial and sequential accessibility of data to be able to obtain a wide area in a limited time. It is also possible to store, collect, retrieve, transform, analyse, and present spatial data using it (Aneesh & Deka, 2015; Kenduiywo et al., 2021). Globally, groundwater sources are usually determined using gis and remote sensing methods (Salem et al., 2019). The remote sensing data and GIS technologies forms combinations with thematic layers to perform the analysis of the potential areas of the groundwater with the undoubtedly useful outcomes according to the analytic hierarchy process technique (Benjmel et al., 2020).

Geographic Information Systems (GIS) is required to analyze, monitor plan and manage the development as well as usage of the groundwater. They enable an evaluation of changes in the local and micro scales of the factors affecting the time and space patterns of the groundwater (Islam et al., 2018). With the remotely data, there are million opportunities that the GIS application can be able to determine the ground water potential zone of agriculture and sustainable development. According to Forkuor et al. (2013), the groundwater potential areas are prone to be caused due to the existence of a few factors like; geomorphology, lineament, slope, elevation, soil type, drainage pattern, land use/land cover, rainfall etc. Remote sensing and GIS are also reported to be able to be related with the local knowledge and rapid and participatory approach of resources assessment by the recent research (Senthil Kumar & Shankar, 2014). A geographic information system was prepared with seven thematic layers, namely slope lithology, drainage density, soil, net recharge, geomorphology, and surface water bodies to identify the zone of the groundwater potential in a soft rock within the Midnapur District of the West Bengal state in India. To determine the relevance of every theme map, the estimate of groundwater potentials was used (Shahid et al., 2000).

All these factors indicate that it is in the central part of the study area that the ground water sources are abundant and developable. The findings of this research indicate that the applied approach is efficient and a credible tool of a swift and correct evaluation of groundwater resources. The work could serve as a systematic reference manual to researchers in later studies with respect to the area concerning water-related information. GIS is also used in the process of determining the likely impacts of climate change on ground water resources. AHP modeling would be used in this area of study in which the input to overall sustainability and vulnerability to ground water are evaluated. Sustainable groundwater management plans can be proposed by the GIS, remote sensing, and AHP modeling techniques. The conclusion of the study can be useful in the water scarcity issues in the Multan District as well as the sustainable use of ground water resources. The findings of the research can be used by the stakeholders in their decisions made regarding the ground water development and management. The aim of the research is to estimate groundwater potential zone based on the AHP model with the help of remote sensing and GIS.

2. Materials and Methods

2.1. Study Area

The research project's study area is District Multan, which is situated in Punjab Province's southern region at latitude 30.157458 and longitude 71.5249154. Multan District is one of Pakistan's five major centers in 2023. Multan District is expected to have 2.2 million residents by 2023, with a growth rate of 2.33%. The Chenab River is where it is situated. Multan is 0 feet above sea level and experiences a subtropical desert climate. Temperature of the district’s annual is 32.96 ℃ and it is 12.07% larger than Pakistan’s average and humidity is 35.5%. Rainy days are 50.43 per year, and District Multan typically receives 23.57 millimeters (0.93 inches) of precipitation. Because to development and a subpar sewage infrastructure, the groundwater in the Multan district is not clean. We were able to locate possible groundwater sources in Multan District thanks to our study.

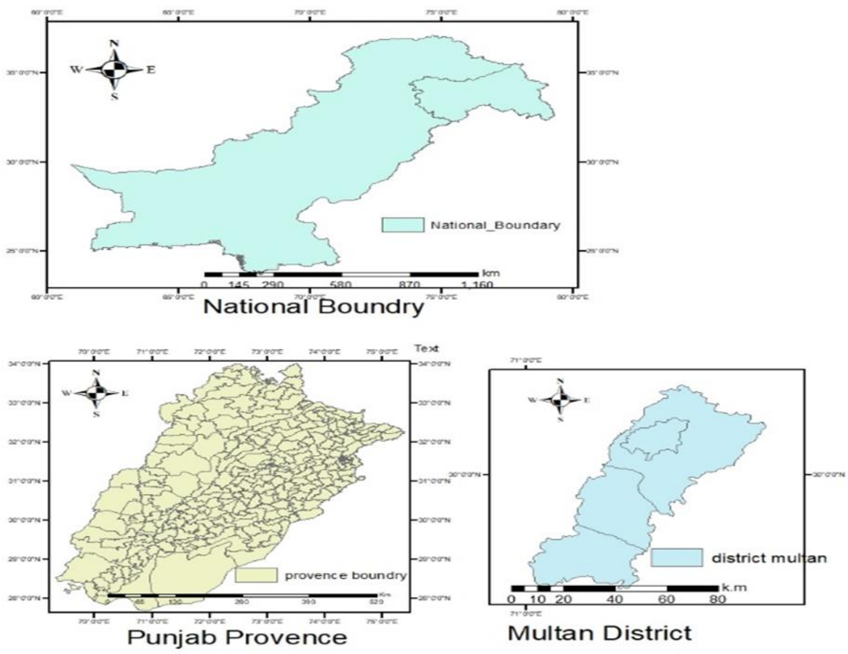
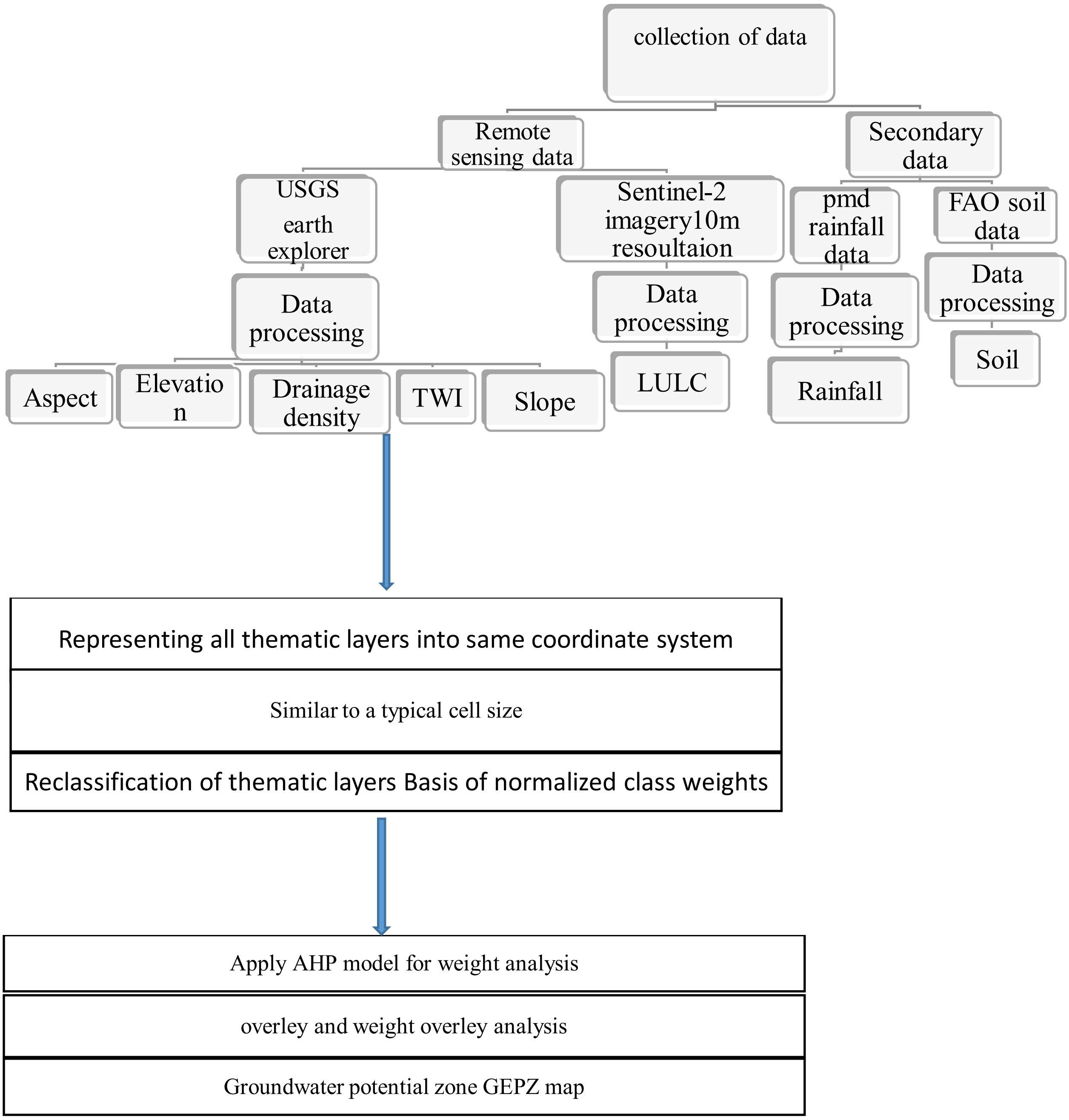


Figure 1: Study Area Map of Multan, Pakistan

2.2. Methodoly

2.2.1. Development of Data

For the District of Multan, a potential groundwater zone has been predicted. Data is gathered for this purpose from two primary sources: SRTM (free source) and USGS Google Earth Explorer (free source). ArcGIS groundwater potential zone modeling has been discovered by the use of spatial data models and several characteristics, including drainage density, slope, soil map, TWI, LULC, aspect map, and elevation map. ENVI 4.7 was used for the research area's shape file.



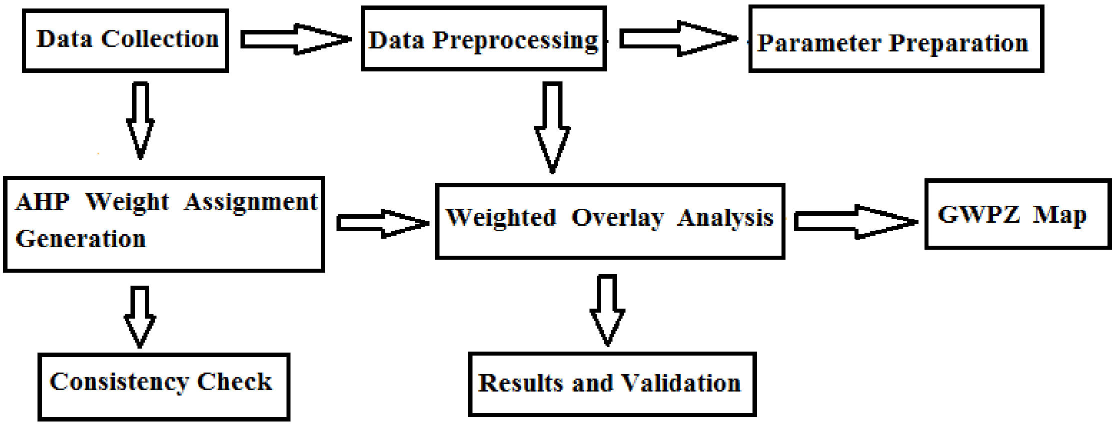


Figure 2: Flow Chart for Data Collection and Preparedness

2.2.2. Generating Spatial Dataset

For the preparation of proper parameter for the spatial dataset is the challenging part for groundwater potential zone modelling. Preparation of these parameters used for the AHP modelling, involved the satellite images, soil data, LULC data, previous published data and from many other sources are mentioned in table 1.

Table 1
Data Sources and Parameters Used for Groundwater Potential Modelling

Parameter	Data Source	Resolution /Scale	Format	Purpose/Justification
Drainage Density	USGS, SRTM (Shuttle Radar Topography Mission)	30m	Raster	Analyzing surface water flow and infiltration capacity.
LULC (Land Use)	Sentinel-2 Imagery	10m	Raster	Assessing the impact of vegetation and urbanization on groundwater recharge.
Rainfall	Pakistan Meteorological Department (PMD)	1:100,000	Raster	Quantifying natural groundwater recharge through precipitation.
Soil Texture	FAO (Food and Agriculture Organization)	1:100,000	Vector	Evaluating infiltration and water-holding capacity of soils.
TWI (Topographic Wetness Index)	Derived from DEM (Digital Elevation Model)	30m	Raster	Assessing potential water accumulation areas based on terrain.
Slope	SRTM (DEM data)	30m	Raster	Understanding runoff and infiltration dynamics.
Aspect	SRTM (DEM data)	30m	Raster	Evaluating the impact of solar exposure on moisture retention.
Elevation	SRTM (DEM data)	30m	Raster	Analyzing the impact of elevation on groundwater recharge potential.

2.3. Statistical Analysis

2.3.1. Analytical Hierarchy Process (AHP) Model

The model of Analytical Hierarchy Process (AHP) was created in the frame of the current research to identify a relative significance of every parameter of the groundwater recharge zones assignment. A method of AHP was also chosen to give an evaluation of the potential ground water zones leveraging on the use of advanced techniques and applications such as remote sensing and GIS, electrical resistivity and Multi-Criteria Decision Analysis (MCDA) in assessing the potential ground water zones (Mallick et al., 2019). The weighting was applied to the majority of the thematic layers including the precipitation, land use and land cover (LULC), stratification, the drainage density, the soil type, the soil texture and the slope as they were of influence to the groundwater potential (Jhariya et al., 2021; Saranya & Saravanan, 2020). To model ground water there is the need to identify the potential zone of ground water that is based on eight factors divided into three categories: geology, soil type, slope, land cover/use, elevation, and rainfall (Pande et al., 2021). These thematic maps are superimposed by the use of weighted overlay analysis in an effort to capture the prospects of groundwater catchments. The indication by the results shows that there is a strong positive correlation that will assist in the successful utilisation of groundwater in this field of research. Modeling ground water Using the parameters that affect the ground water potentiality, the AHP model is that which is used to model the ground water (Priya et al., 2022).

Analytical Hierarchy Process (AHP) is quite a useful method of multi-parametric evaluation (Saaty, 1994). Of specific intrusiveness are environmental modeling and spatial analysis. AHP enables sorting and ranking many criteria in a hierarchical way, and the relative values of each one of variables, which may affect the groundwater potential, are obvious. The tiers towards the hierarchy of the studied work are three-fold in its arrangement; the first goal of the groundwater potential zoning, the criteria (drainage density, land cover and land use, rainfall, soil texture, topographic wetness index, slope, aspect and elevation) and the final product, the potential zones. Prior to ranking and weight assignment in the current research, a number of other researches of similar nature that had been carried out in the past, were painstakingly researched in a way that is aiming to ensure that ranking and weights of items in various areas and settings are adequately considered in ensuring value judgment.

The study has ranked the effects of different factors in the environment in determining the groundwater recharge potential by using Analytical Hierarchy Process (AHP) model. In order to have an idea of how each factor like the density of drainage, land use/land cover (LULC), the slope, and the rainfall is relatively important, one started creating a pairwise comparison matrix. The method developed by Saaty was used to obtain weights related to each of the parameters, Consistency Index (CI) and Consistency Ratio (CR) were computed to determine the consistency of such ratings, and in case the CR was bigger than an acceptable ratio of 0.1, the corrections were made. On validation, the weighted parameters have been uploaded to a Geographic Information System (GIS) by which a weighted overlay analysis has been performed which has come up with a total ground water potential zoning map on the superimposition of all theme maps. MCDA and remote sensing enhanced this type of spatial analysis, consequently offering the instrument of trustworthiness in the sense that people were able to select the most suitable locations where to replenish the ground water hence making the process to be evidence-based and methodologically acceptable. Pairwise comparison matrix build is one of the steps through the procedure.

2.3.2. Calculate Consistency Ratio and Adjustment

Assign weights to every parameter in a pairwise comparison table. The parameters are rated on the basis of the influence they create in the recharge of groundwater, after comparing one with the other. This matrix provides the relative weights of each of the criteria by calculation of eigenvalues. The primary eigenvalue is used in order to ensure that the conclusions derived out of the comparisons are consistent. Subsequently a consistency ratio (CR) is calculated; a CR of less than 0.1 is considered satisfactory; a higher value causes the comparisons to be readdressed and adjusted. This strategy will ensure the accuracy of the weights associated with every parameter and scientific corroboration.

Once validated the weights are, subsequently, incorporated in an environment of Geographic Information System (GIS) through a weighted overlay analysis. Thus, all the thematic layers could be overlapped to space domain to provide the closer description of the groundwater potential zones of Multan District. The accuracy with which the groundwater evaluation could be done and the stability of the groundwater evaluation is increased by the capability of the AHP technique to augment the opinion of the expert with the quantitative analysis that creates the effective instrument of management and planning of the resources. Such methods as the Analytical Hierarchy Process (AHP) are highly feasible when it comes to multi-parametric evaluation (Saaty, 1994). Since it was possible to sort out the criteria according to hierarchical regimes with the assistance of a pairwise comparison matrix, the subject has been identified, its priority, and rank. The practices proposed by Saaty (1994) were adhered in calculating the Consistency Index and the Consistency Ratio. AHP has been used in a manner which ranks the theme and classes individually, in terms of weight. (Malczewski & Rinner, 2015) note that the well-known method of multi-criteria decision investigation is the AHP approach, which can be used in the investigation of appropriateness, site selection, and natural resource management. Before ranking and weights in the present article, several different articles published in the past were analyzed thoroughly to make sure that ranking and weights of different elements in different locations and circumstances were taken into the analysis correctly. The parameter weight is determined using numerous methods. Here the method of consistency ratio was used.

2.3.3. Consistency Ratio Calculation

The appropriateness for each parameter weight is estimated using this computation. Less than 10% should be the consistency ratio and the weight of the parameter regarded as constant for this purpose. The following formula can be used to get the consistency ratio (Saaty, 1994).

$$CR = CI/RI \quad (1)$$

The random index in this equation is denoted by RI, and the consistency index by CI. According to the table, the RI value for the 8 parameter is 1.41.

Table 2
Random Index (RI) Values for "n" Parameters.

N	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.92	1.12	1.24	1.32	1.41	1.45

Random index values
We also measured CI value by using the

$$CI = \frac{\lambda max - n}{n-1} \quad (2)$$

In this case, n refers to a sum of all the parameters that this research is using whereas 1 max is an eigenvalue of the matrix. The inconsistency is acceptable provided that the consistency ratio of the formulation does not increase to over 0.1, in case it surpasses 10 percent, there is a need to rectify the particular decision accordingly.

Table 3
Preference Matrix
A revision of the preference matrix is recommended if CR > 0.1

Parameter	Drainage Density	LULC	Slope	Rainfall	TWI	Soil Map	Elevation	Aspect	Total
Drainage Density	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
LULC	0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
Slope	0.333	0.5	1.0	2.0	3.0	4.0	5.0	5.0	6.0
Rainfall	0.25	0.333	0.5	1.0	2.0	3.0	5.0	5.0	6.0
TWI	0.2	0.25	0.333	0.5	1.0	2.0	3.0	4.0	5.0
Soil Map	0.167	0.2	0.25	0.333	0.5	1.0	2.0	3.0	4.0
Elevation	0.143	0.167	0.2	0.2	0.33	0.5	1.0	2.0	3.0
Aspect	0.125	0.143	0.2	0.2	0.25	0.333	0.5	1.0	2.0

The last equation which was used to model the groundwater potential zone by the application of the AHP approach is provided below.

$$GWPI = (DDw) \times (DDr) + (LULCw) \times (LULCr) + (SLw) \times (SLr) + (RFw) \times (RFr) + (TWIw) \times (TWIr) + (Sw) \times (Sr) + (Elw) \times (ELr) + (ASw) \times (ASr) \quad (3)$$

In the research region, DD stands for drainage density, LULC for land cover and use, SL for slope, RF for rainfall, TWI for topographic wetness index, S for soil map, EL for elevation, and AS for aspect map.

Table 4
Criteria Weight of Thematic Layers

Parameters	Criteria weight
Drainage density	31.1895
LULC	22.2417
Slope	15.1084
Rainfall	11.1363
TWI	7.3971
Soil	5.0763
Elevation	3.4494
Aspect	3.5398

3. Results and Discussion

The subsurface water resource zone was characterized through remote sensing imagery, which was also employed to establish parameters pertinent to the desired results. Relative importance values were assigned to determine GWPS following the integration of multiple thematic datasets through Saaty's Multi-Criteria Decision-Making framework. The GWPS framework was evaluated against measurements from boreholes. The central section of the research area is identified as an appropriate region for aquifer development due to the stratigraphic arrangement of the alluvial basin, minimal elevation, moderate to significant drainage concentration, and additional topographical factors. These characteristics collectively indicate that the research area's midpoint contains valuable aquifer resources and development opportunities. This research demonstrates that the implemented methodology provides a dependable approach for accurately and productively evaluating groundwater assets with strong reliability measures. This investigation could serve as a methodical reference for subsequent research on hydrological resources, particularly in drought-prone environments.

3.1. Preparation of Maps

3.1.1. Elevation Map

One topographical element that is thought to be crucial for locating groundwater is elevation. Elevation changes may influence the climatic conditions, which subsequently may modify precipitation distributions, pedological properties, plant coverage, terrain surface, and flora diversity. Additionally, it governs the occurrence and aquifer replenishment capacity, which makes it significant (Mallick et al., 2014). One critical component that manages the movement of water through the terrestrial environment is topographic height. Lower elevation plains tend to retain water longer, which increases groundwater recharge (Benjmel et al., 2020). The study region's elevation extends from 79 to 156. In this District Multan research study, the elevation criterion weight is 3.4449. After gathering elevation data in raster form from the SRTM DEM, it is processed further in ArcGIS, where various modifications are made, and finally an elevation image is produced.

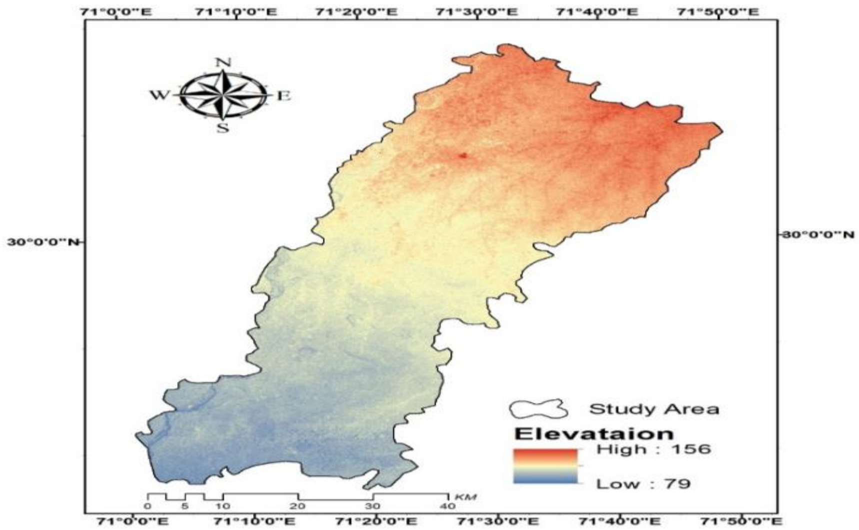


Figure 3: Elevation Map of the Study Area

3.1.2. Slope Map

The factor that affects runoff and infiltration in a location is the area's slope. While slope has an inverse influence on infiltration, it is directly proportional to surface runoff. Accordingly, the rate of surface runoff increases with slope steepness, but the rate of infiltration tends to decrease (Pande et al., 2021). Steeper slopes have the lowest ranking because they can create a little amount of groundwater recharge through runoff, whereas flate slopes have a high rating because they can store water for a long time. The maximum eigenvalue in this study is 0.4844, the criteria weight is 15.1084, and the slope ranges from 0 to 33.19. The SRTM DEM data is used to create the slope map, and ArcGIS 10.8.2 is used for additional processing.

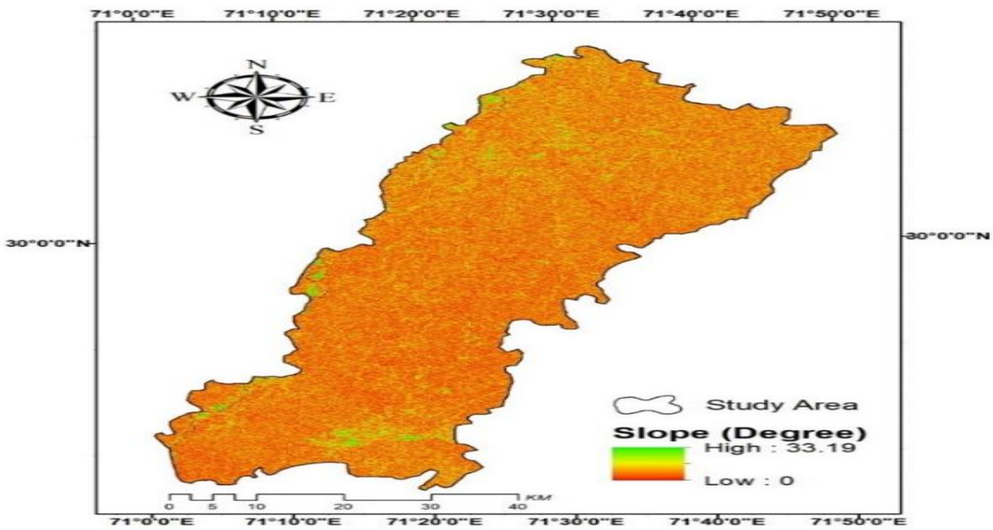


Figure 4: Slope Map of Study Area

3.1.3. Aspect Map

The topographic orientation demonstrates the consequences of different slope directions on wind velocity, solar energy, rainfall, and land use/land cover. As noted by Solomon and Quiel (2006), these parameters also influence the moisture content within sedimentary porous structures, which could potentially impact the region's subsurface water reserves. The directional facing of inclines significantly affects both water penetration rates and the global water resource which quantifies solar energy input. The digital information gathered consists of digital elevation model data representing satellite imagery that is subsequently transferred to ArcGIS software to produce the definitive directional exposure map. Its directional values range from -1 to 359.11 and the importance factor of this parameter is 3.5298.

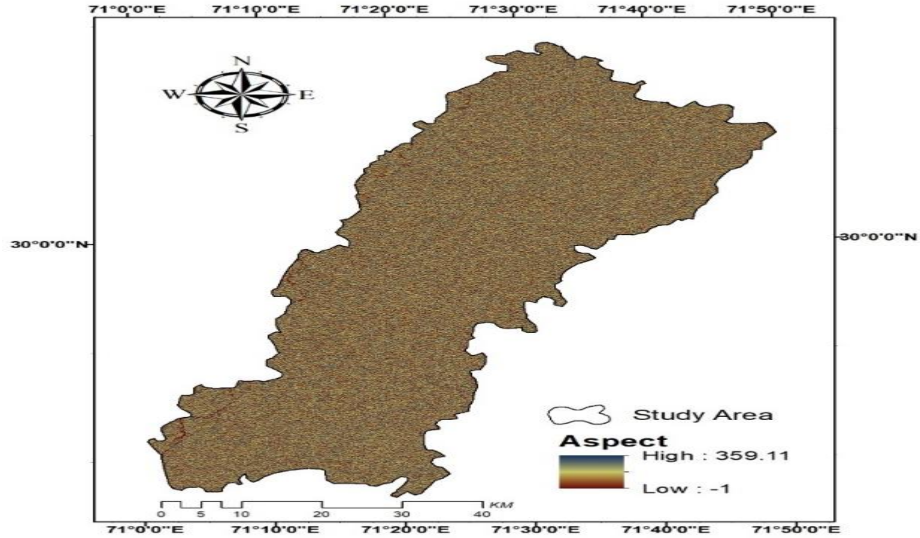


Figure 5: Aspect Map of Study Area

3.1.4.Topography Wetness Index Map

TWI is another important element that is adopted in arriving at the topographical control. Basically, TWI can be employed to determine the quantity of available water in the study area and this leads to topography through water accumulation (Biswas et al., 2020). Spatial distribution of water put out to the surface through run off could be regulated via observation of TWI. The parameter TWI related to water flow can be calculated as in the following formula.

T.W.I = 1n A/ tan ß (4)

Where the term, represents a stand of the catchment in the equation, and ß a specific angle of the slope. When the supply of water is high the T.W.I is higher as compared to low supply of water. The value of criterion weight is 7.3971 and the highest eigen value of TWI is 0.2372. The TWI map is constructed with the help of ArcGIS.

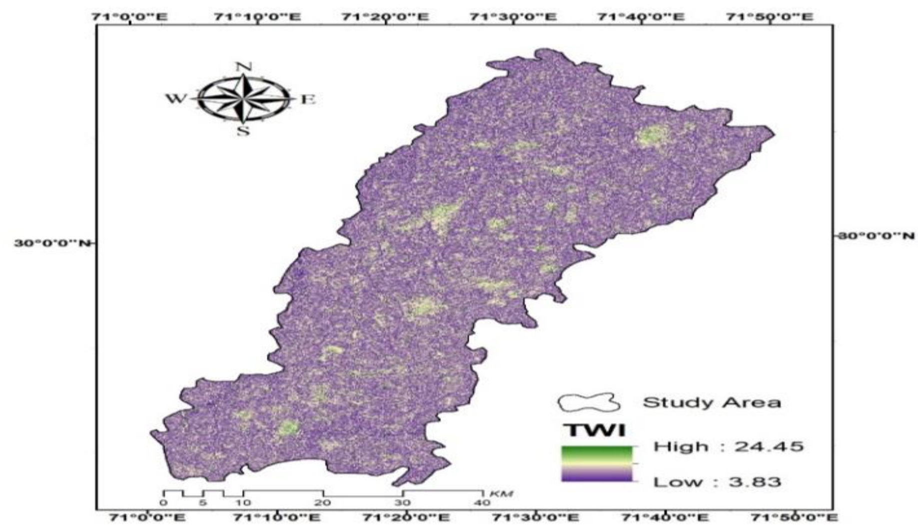


Figure 6: TWI Map of Study Area

3.1.5. Rainfall Map

A critical element in governing groundwater replenishment is precipitation, which plays an essential role in the hydrological process. It substantially affects the pace of surface water flow and permeation into soil (Castillo et al., 2021). Precipitation contributes vitally to maintaining the entire water cycle by refreshing and collecting new water on Earth's surface. The amount of precipitation serves a fundamental function in groundwater replenishment since it determines the quantity of water that will seep into the ground (Abuzied et al., 2015). Both the length and quantity of precipitation are significant as they establish the water volume that will accumulate and flow across the designated area. The precipitation measurements utilized in the study range from 266.65 to 306.65. Greater precipitation enhances groundwater potential. The criterion weight equals 11.1363 and the principal eigenvalue of the eigenvector equals 0.3571. The precipitation distribution chart is developed for the study location within the precipitation region, which is subsequently processed in ArcGIS using the inverse distance weight technique.

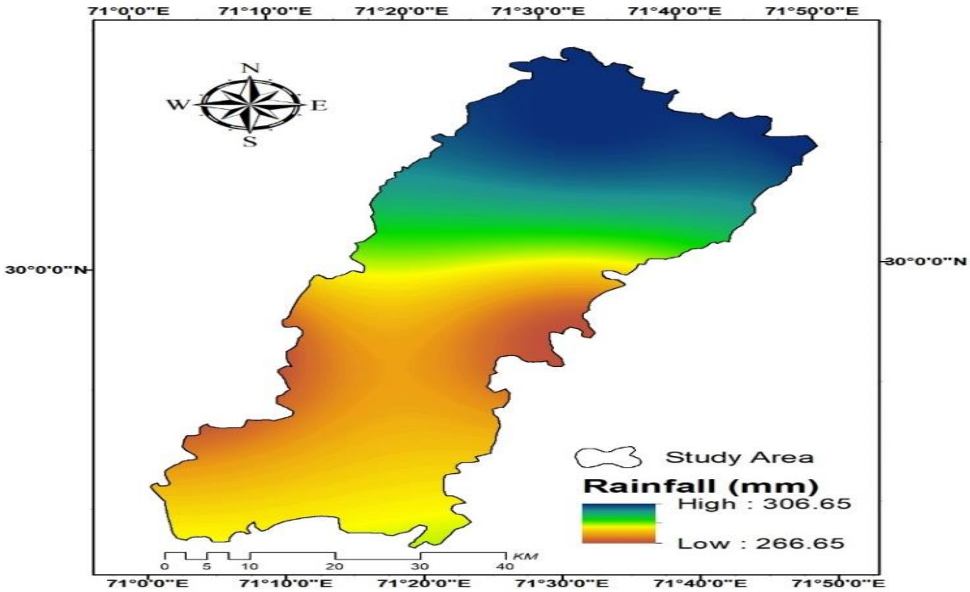


Figure 7: Rainfall Map of Study Area

3.1.6. Land Use / Land Cover Map

The data about the soil moisture, permeability, runoff and percolation depend on the type of land use of the research area (Ahmed & Sajjad, 2018). Biswas et al. (2020) state that it is also used to gauge the incident and expansion of the groundwater potential domain. Forest areas tend to be the most appropriate area to penetrate into the ground water as compared to the built up areas and flowlands, which enhance fast rates of runoff of the region. According to the type of land it is, there will be an infiltration and runoff capabilities. The rate of infiltration is greater than the rate of runoff in the study area since most part of the area is covered with vegetation. Bare soil has a low value of the groundwater infiltration as well as built-up areas. This LULC map is generated by means of ArcGIS 10.8.2 after generating it using Sentinel-2 images (10 m). District Multan is mostly vegetative hence there is greater infiltration of ground water here. The weight of the LULC map is 22.2417, and its maximum value of an engine is the value of 0.7131.

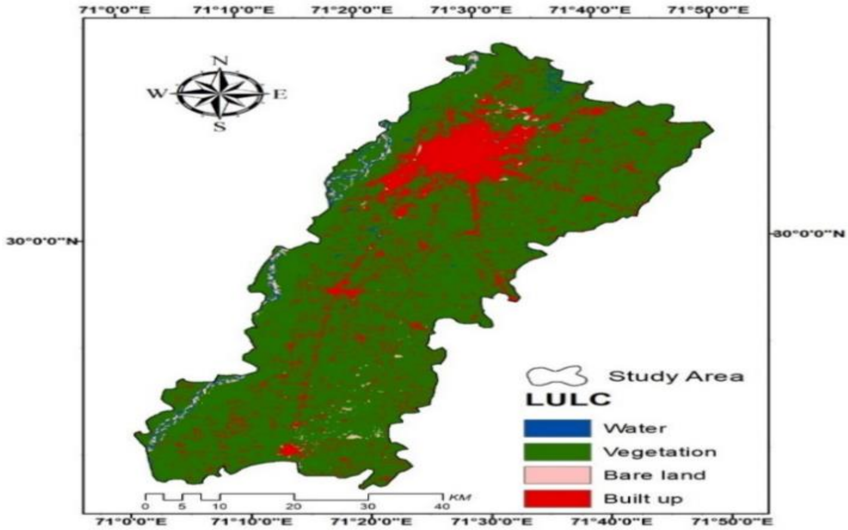


Figure 8: Land Use and Landcover Map of Study Area

3.1.7. Soil Texture Map

Water flows through the soil layer as it is the uppermost layer of the ground. The permeability of soil and water storing ability determine the infiltration rate (Arivalagan, Kiruthika, et al., 2014; Saranya & Saravanan, 2020). The characteristics of the soil may be used to check the rainfall infiltration, rates of penetration and water capacity. The soil types most widely found in the region of the research were loam and clay, of which loam dominates. Because of its ideal composition and ability to retain water, loam is regarded as the greatest grade soil. A primary geomorphological element influencing groundwater replenishment is terrain composition. Particle dimensions, water percolation speed, soil classification, and humidity levels represent several variables that significantly influence groundwater replenishment rates. The Food and Agriculture Organization (FAO) supplied the earth material information, and the weighting criterion assigned to soil texture is 5.0763. ArcGIS 10.8.2 was used to finish the mapping process. Below is a representation of the terrestrial composition.

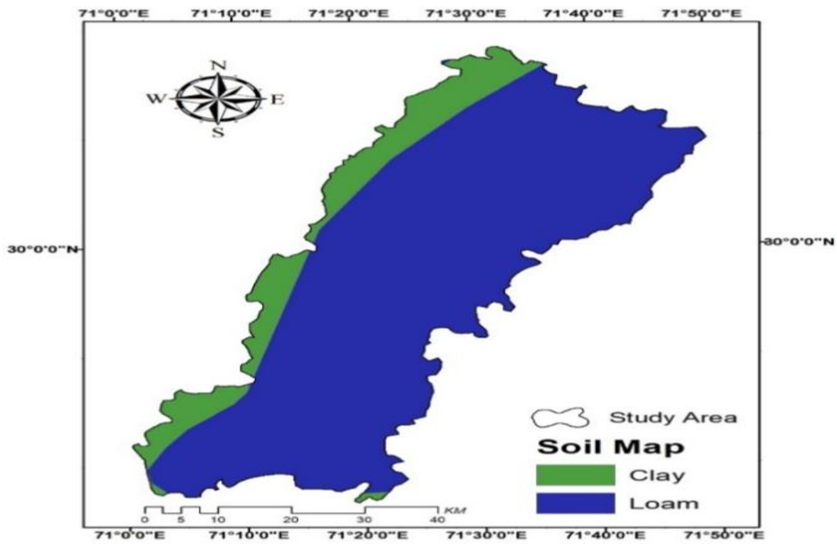


Figure 9: Soil Map of Study Area

3.1.8. Drainage Density Map

The most crucial metric for assessing the potential groundwater circulation in a region is drainage density (Arshad et al., 2020). It is the spatial circulation of every drainage station in a given region. Permeability and drainage density have an inverse relationship that influences runoff and infiltration volume (Adiat et al., 2012; Ibrahim-Bathis & Ahmed, 2016). The infiltration rate and groundwater potential system indicate high sources if the drainage density value is low. In this study, low drainage density is more advantageous because of the high groundwater potentiality. A region's drainage density is influenced by its topography, geology, land use, and geomorphology (Siva et al., 2017). The research area's drainage density ranges from 0 to 0.87 m/m2. This work's criterion weight is 31.1895. Due to the region's level topography, the majority of the whole area has low to extremely low drainage density. The findings indicate that a high GWPS value is implied by a low drainage density. Figure 4.8 displays the drainage density map.

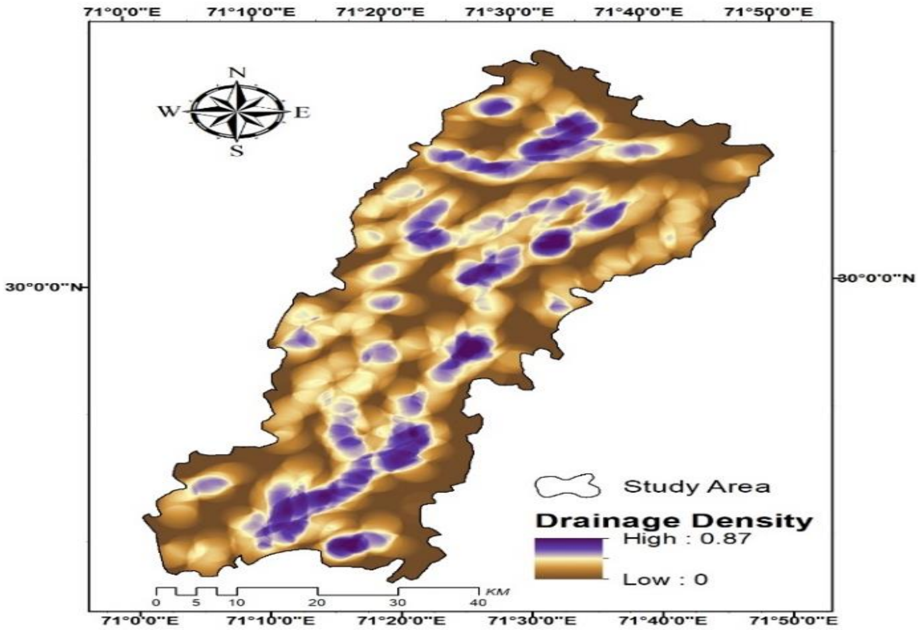


Figure 10: Drainage Density Map of Study Area

3.1.9. Groundwater Potential Zone

Eight thematic strata were merged to establish a subsurface water resource potential region (GWPZ) visualization for the study area. As indicated in Table 2, multi-criteria overlay methodology was employed to assign significance values to these strata. All parameters were integrated in matrix structure to generate the GWPZ visualization. Utilizing software specifically engineered for this application, the multi-criteria overlay methodology was implemented in ArcGIS 10.8.2. The Multan District's groundwater potential zone (GWPZ) visualization delineates four capability categories: minimal, intermediate, substantial, and exceptionally substantial. The visualization indicates that substantial portions of the area exhibit significant groundwater potential due to abundant vegetation and predominantly flat, minimally rocky landscape. The definitive GWPZ visualization was developed by integrating the eight thematic strata following their transformation into matrix configuration, as demonstrated in Table 2. Through application of the Analytical Hierarchy Process (AHP), this visualization functions as a framework to assess the Multan District's groundwater potential. This conclusive visualization, produced through implementation of the AHP framework, predominantly identifies regions in the District of Multan with significant potential levels. A modification of the preference matrix is suggested if $CR > 0.1$.

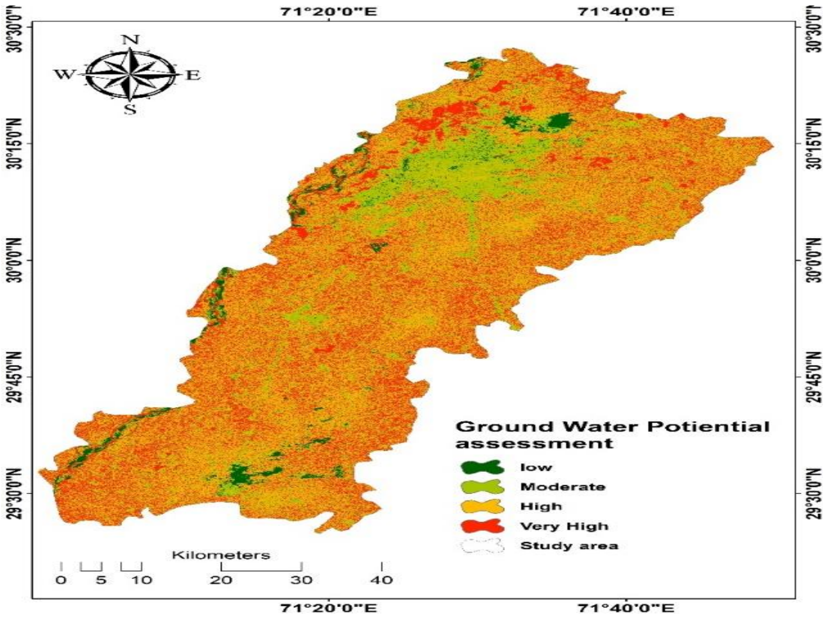


Figure 11: Ground Water Potential Assessment

3.2. Discussion

The integration of GIS and the Analytical Hierarchical Process (AHP) was an efficient method of establishing groundwater potential zones (GWPZ) in District Multan. The results contributed to the idea that when there is a low drainage density, it promotes a groundwater recharge and improved infiltration due to the decreased surface runoff and smoother topography (Ibrahim-Bathis & Ahmed, 2016). The most significant factor was the drainage density (criteria weight: 31.19). The finding is in conformity with the previous studies by Adiat et al. (2012) where the negative relationship between ground water availability and drainage density was highlighted. Similarly, slope (weight: 15.11) and land use/land cover (LULC) (weigh: 22.24) had a significant effect on groundwater potential. Vegetated areas and low slope cause groundwater recharge to increase as they contribute to the increased infiltration and reduced runoff (Ahmed & Sajjad, 2018; Pande et al., 2021). Conversely populated and arid regions on the other hand, as was also evident in the area of research, are usually restricting to in-filtration and promote surface water movement.

There was a crucial impact of recharging potential by rainy layer (11.13). The zones that had high potential ground water in the study area were positively correlated to those areas that had high rain fall. This is in line with the research article by Abuzied et al. (2015) and Castillo et al. (2021) that emphasized the significant role that the duration and intensity of precipitation would serve in influencing the infiltration and recharge rate. In spite of their relatively lower weights, Topographic Wetness Index (TWI), soil texture, elevation, and aspect also contributed to the model, which reveals their supportive role in the patterns of water distribution, percolation, and accumulation (Benjmel et al., 2020; Biswas et al., 2020; Solomon & Quiel, 2006). Since most of the area was within the high potential category, the GWPZ map classified the area into four potential categories namely low, moderate, high and very high potentials. This is attributed to favorable geomorphology (particularly in the middle of the district) in the form of loamy soil, flat topography and vegetation. These results were compared with the available tube well data in order to establish the correctness and dependability of the model (Arivalagan, Singaraj, et al., 2014).

Also, the AHP method and subsequent use of thematic layers to the decision process cut down on subjective nature of weighting and ensured uniformity that made the final groundwater potential zone map more credible. The Consistency Ratio (CR) assured the dependability of the pairwise comparison matrix since it remained within quite manageable limits ($CR < 0.1$). This further indicated that the parameters used were logically accurate. AHP model is a powerful tool in regional water resource planning and policy-making due to its flexibility that allows it to be adapted and be reused in different geographic locations. This approach not only encourages the management of groundwater efficiency but also environmentally sustainable planning of agricultural situations and urban developments and methods of disaster reduction in water-stressed regions such as southern Punjab. These types of data-based assessments are increasingly becoming more relevant in guiding both the short-term engagements as well as long-term water governance infrastructures as groundwater is increasingly being challenged by over extraction and climate changes (Biswas et al., 2020).

This study had eight layers of themes that were overlaid as weighted overlay that facilitated easier determination of potential zones prone to groundwater in the Multan District. Analytical Hierarchy Process (AHP) was used to base on the relative weight that should be given to each of the parameters considering the extent that it will affect the groundwater supply. The findings proved the credibility of this integrative method since there was a significant positive correlation between the weighted parameters and the geographic distribution of groundwater zone (Priya et al., 2022). Due to the terrain alteration, underlying hydrogeological formations, and climatic trends, supply of ground water often changes both geographically, as well as temporally in semi-arid regions, such as Multan. To have a sustainable water management especially in groundwater potential zones, it is essential that such areas can be well defined. Successful application of GIS, remote sensing, AHP, etc. in the arid and semi-arid terrain has verified the versatility and effectiveness of this methodology, including a study conducted in the semi-arid San Luis Potos, Mexico, that was able to map groundwater potential using GIS, satellite images, and AHP methods with great precision (Castillo et al., 2021).

4. Conclusion

The Analytic Hierarchy Process (AHP) methodology, satellite-based data collection and Geographic Information Systems (GIS) constitute crucial components employed in groundwater modeling research. Sustainable resource governance plays an essential function amid increasing requirements for groundwater resources resulting from industrial development and demographic expansion. This research utilizes AHP to determine potential groundwater availability zones in District Multan through the integration of GIS capabilities and satellite-derived data. Key variables assessed include terrain gradient, watershed network density, altitude, precipitation patterns, Topographical Moisture Index (TWI), directional exposure, and terrestrial surface characteristics (LULC). These parameters were combined through Eigen Vector Values and weighted overlay techniques where thematic elements received specific importance values per stratum. Findings indicate that steeper gradients reduce aquifer replenishment, while areas featuring vegetation and loamy soil composition demonstrate significant water penetration capacity. The AHP methodology identified four groundwater classification zones: minimal, moderate, substantial, and exceptional potential. The predominant portion of Multan was categorized within substantial-potential territories. Precise locational information derived from GIS technologies and remote observation techniques enabled effective cartographic representation and evaluation. While identifying significant factors such as gradient, altitude, and drainage patterns in groundwater distribution patterns, this investigation underscores the importance of thematic stratification in hydrological modeling. These conclusions assist in recognizing prospective zones and improving resource quantity and quality, supporting evidence-based policy formulation for sustainable groundwater administration.

Authors Contribution
Anila Anwar: Data interpretation and map generation
Awais Munir: Conceptualization, analyzed the data, and prepared the first draft of manuscript.
Noor Fatima: methodology design and supervised field data collection.
Asma Majeed: Critical revision, incorporation of intellectual content and final editing.
Hafiza Momina Rafiq: Methodology design and supervised field data collection.
Iftikhar Ahmed: Critical revision, incorporation of intellectual content and final editing.

Conflict of Interests/Disclosures

The authors declared no potential conflicts of interest w.r.t. the research, authorship and/or publication of this article.

References

Abuzied, S. M., Yuan, M., Ibrahim, S. K., Kaiser, M. F., & Seleem, T. A. (2015). Delineation of Groundwater Potential Zones in Nuweiba Area (Egypt) Using Remote Sensing and Gis Techniques. *International Journal of Signal Processing Systems*, *4*(2). https://doi.org/10.12720/ijsps.4.2.109-117

Adiat, K. A. N., Nawawi, M. N. M., & Abdullah, K. (2012). Assessing the Accuracy of Gis-Based Elementary Multi Criteria Decision Analysis as a Spatial Prediction Tool – a Case of Predicting Potential Zones of Sustainable Groundwater Resources. *Journal of Hydrology*, *440-441*, 75-89. https://doi.org/10.1016/j.jhydrol.2012.03.028

Ahmed, I., Abbasi, G., Jamil, M., & Malik, Z. (2022). Exogenous Methyl Jasmonate Acclimatemorpho-Physiological, Ionic and Gas Exchangeattributes of Wheat Genotypes(*Triticum Aestivum* L.) under Salt Stress. *Polish Journal of Environmental Studies*, *32*(1), 1-14. https://doi.org/10.15244/pjoes/152882

Ahmed, R., & Sajjad, H. (2018). Analyzing Factors of Groundwater Potential and Its Relation with Population in the Lower Barpani Watershed, Assam, India. *Natural Resources Research*, *27*(4), 503-515. https://doi.org/10.1007/s11053-017-9367-y

Al-Abadi, A., & Al-Shamma'a, A. (2014). Groundwater Potential Mapping of the Major Aquifer in Northeastern Missan Governorate, South of Iraq by Using Analytical Hierarchy Process and Gis. *J Environ Earth Sci*, *10*, 125-149.

Al-Abadi, A. M. (2017). Modeling of Groundwater Productivity in Northeastern Wasit Governorate, Iraq Using Frequency Ratio and Shannon's Entropy Models. *Applied Water Science*, *7*(2), 699-716. https://doi.org/10.1007/s13201-015-0283-1

Al-Djazouli, M. O., Elmorabiti, K., Rahimi, A., Amellah, O., & Fadil, O. A. M. (2021). Delineating of Groundwater Potential Zones Based on Remote Sensing, Gis and Analytical Hierarchical Process: A Case of Waddai, Eastern Chad. *GeoJournal*, *86*(4), 1881-1894. https://doi.org/10.1007/s10708-020-10160-0

Al-Manmi, D. A. M., & Rauf, L. F. (2016). Groundwater Potential Mapping Using Remote Sensing and Gis-Based, in Halabja City, Kurdistan, Iraq. *Arabian Journal of Geosciences*, *9*(5), 357. https://doi.org/10.1007/s12517-016-2385-y

Anbazhagan, S., & Jothibasu, A. (2016). Geoinformatics in Groundwater Potential Mapping and Sustainable Development: A Case Study from Southern India. *Hydrological Sciences Journal*, *61*(6), 1109-1123. https://doi.org/10.1080/02626667.2014.990966

Aneesh, R., & Deka, P. C. (2015). Groundwater Potential Recharge Zonation of Bengaluru Urban District—a Gis Based Analytic Hierarchy Process (Ahp) Technique Approach. *Int Adv Res J Sci Eng Technol*, *2*(6), 129-136.

Arivalagan, P., Singaraj, D., Haridass, V., & Kaliannan, T. (2014). Removal of Cadmium from Aqueous Solution by Batch Studies Using Bacillus Cereus. *Ecological Engineering*, *71*, 728-735. https://doi.org/https://doi.org/10.1016/j.ecoleng.2014.08.005

Arivalagan, S., Kiruthika, A., & Sureshbabu, S. (2014). Delineation of Groundwater Potential Zones Using Rs and Gis Techniques: A Case Study for Eastern Part of Krishnagiri District, Tamil Nadu. *International Journal of Advanced Research in Science, Engineering and Technology*, *3*, 51-59.

Arshad, A., Zhang, Z., Zhang, W., & Dilawar, A. (2020). Mapping Favorable Groundwater Potential Recharge Zones Using a Gis-Based Analytical Hierarchical Process and Probability Frequency Ratio Model: A Case Study from an Agro-Urban Region of Pakistan. *Geoscience Frontiers*, *11*(5), 1805-1819. https://doi.org/10.1016/j.gsf.2019.12.013

Azizullah, A., Khattak, M. N. K., Richter, P., & Häder, D.-P. (2011). Water Pollution in Pakistan and Its Impact on Public Health — a Review. *Environment International*, *37*(2), 479-497. https://doi.org/10.1016/j.envint.2010.10.007

Bashir, A., Shehzad, M. A., Hussain, I., Rehmani, M. I. A., & Bhatti, S. H. (2019). Reservoir Inflow Prediction by Ensembling Wavelet and Bootstrap Techniques to Multiple Linear

Regression Model. *Water Resources Management*, *33*(15), 5121-5136. https://doi.org/10.1007/s11269-019-02418-1

Benjmel, K., Amraoui, F., Boutaleb, S., Ouchchen, M., Tahiri, A., & Touab, A. (2020). Mapping of Groundwater Potential Zones in Crystalline Terrain Using Remote Sensing, Gis Techniques, and Multicriteria Data Analysis (Case of the Ighrem Region, Western Anti-Atlas, Morocco). *Water*, *12*(2), 471. https://doi.org/10.3390/w12020471

Biswas, S., Mukhopadhyay, B. P., & Bera, A. (2020). Delineating Groundwater Potential Zones of Agriculture Dominated Landscapes Using Gis Based Ahp Techniques: A Case Study from Uttar Dinajpur District, West Bengal. *Environmental Earth Sciences*, *79*(12), 302. https://doi.org/10.1007/s12665-020-09053-9

Castillo, J. L. U., Ramos Leal, J. A., Martínez Cruz, D. A., Cervantes Martínez, A., & Marín Celestino, A. E. (2021). Identification of the Dominant Factors in Groundwater Recharge Process, Using Multivariate Statistical Approaches in a Semi-Arid Region. *Sustainability*, *13*(20), 11543. https://doi.org/10.3390/su132011543

Chang, F.-J., Huang, C.-W., Cheng, S.-T., & Chang, L.-C. (2017). Conservation of Groundwater from over-Exploitation—Scientific Analyses for Groundwater Resources Management. *Science of The Total Environment*, *598*, 828-838. https://doi.org/10.1016/j.scitotenv.2017.04.142

Chenini, I., & Ben Mammou, A. (2010). Groundwater Recharge Study in Arid Region: An Approach Using Gis Techniques and Numerical Modeling. *Computers & Geosciences*, *36*(6), 801-817. https://doi.org/10.1016/j.cageo.2009.06.014

Chowdhury, A., Jha, M. K., Chowdary, V. M., & 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), 231-250. https://doi.org/10.1080/01431160802270131

Forkuor, G., Pavelic, P., Asare, E., & Obuobie, E. (2013). Modelling Potential Areas of Groundwater Development for Agriculture in Northern Ghana Using Gis/Rs. *Hydrological Sciences Journal*, *58*(2), 437-451. https://doi.org/10.1080/02626667.2012.754101

Gang, M., Munir, A., Murtaza, G., Iqbal, R., Majeed, A., Shoaib, M.,…Alkahtani, J. (2024). Agro-Waste-Based Bio-Nanocompositefor the Mitigation of Pb (Ii) Ions from Water. *Polish Journal of Environmental Studies*, *33*(5), 5635-5646. https://doi.org/10.15244/pjoes/183450

Guru, B., Seshan, K., & Bera, S. (2017). Frequency Ratio Model for Groundwater Potential Mapping and Its Sustainable Management in Cold Desert, India. *Journal of King Saud University - Science*, *29*(3), 333-347. https://doi.org/10.1016/j.jksus.2016.08.003

Hashemi, H., Uvo, C. B., & Berndtsson, R. (2015). Coupled Modeling Approach to Assess Climate Change Impacts on Groundwater Recharge and Adaptation in Arid Areas. *Hydrology and Earth System Sciences*, *19*(10), 4165-4181. https://doi.org/10.5194/hess-19-4165-2015

Ibrahim-Bathis, K., & Ahmed, S. A. (2016). Geospatial Technology for Delineating Groundwater Potential Zones in Doddahalla Watershed of Chitradurga District, India. *The Egyptian Journal of Remote Sensing and Space Science*, *19*(2), 223-234. https://doi.org/10.1016/j.ejrs.2016.06.002

Islam, A. R. M. T., Shen, S., Haque, M. A., Bodrud-Doza, M., Maw, K. W., & Habib, M. A. (2018). Assessing Groundwater Quality and Its Sustainability in Joypurhat District of Bangladesh Using Gis and Multivariate Statistical Approaches. *Environment, Development and Sustainability*, *20*(5), 1935-1959. https://doi.org/10.1007/s10668-017-9971-3

Jhariya, D. C., Khan, R., Mondal, K. C., Kumar, T., K., I., & Singh, V. K. (2021). Assessment of Groundwater Potential Zone Using Gis-Based Multi-Influencing Factor (Mif), Multi-Criteria Decision Analysis (Mcda) and Electrical Resistivity Survey Techniques in Raipur City, Chhattisgarh, India. *Journal of Water Supply: Research and Technology-Aqua*, *70*(3), 375-400. https://doi.org/10.2166/aqua.2021.129

Kenduiywo, B. K., Carter, M. R., Ghosh, A., & Hijmans, R. J. (2021). Evaluating the Quality of Remote Sensing Products for Agricultural Index Insurance. *PLOS ONE*, *16*(10), e0258215. https://doi.org/10.1371/journal.pone.0258215

Khair, S. M., Mushtaq, S., Culas, R. J., & Hafeez, M. (2012). Groundwater Markets under the Water Scarcity and Declining Watertable Conditions: The Upland Balochistan Region of Pakistan. *Agricultural Systems*, *107*, 21-32. https://doi.org/10.1016/j.agsy.2011.11.007

Khelifi, E.-A. a. (2019). *Advances in Remote Sensing and Geo Informatics Applications: Proceedings of the 1st Springer Conference of the Arabian Journal of Geosciences (Cajg-1), Tunisia 2018* (H. M. El-Askary, S. Lee, E. Heggy, & B. Pradhan, Eds.). Springer International Publishing.

Lee, S., Kim, Y.-S., & Oh, H.-J. (2012). Application of a Weights-of-Evidence Method and Gis to Regional Groundwater Productivity Potential Mapping. *Journal of Environmental Management*, *96*(1), 91-105. https://doi.org/10.1016/j.jenvman.2011.09.016

Mahalingam, B., & Vinay, M. (2015). Identification of Ground Water Potential Zones Using Gis and Remote Sensing Techniques: A Case Study of Mysore Taluk-Karnataka. *International journal of Geomatics and Geosciences*, *5*(3), 393-403.

Malczewski, J., & Rinner, C. (2015). Development of Gis-Mcda. In *Multicriteria Decision Analysis in Geographic Information Science* (pp. 55-77). Springer Berlin Heidelberg.

Mallick, J., Al-Wadi, H., Rahman, A., & Ahmed, M. (2014). Landscape Dynamic Characteristics Using Satellite Data for a Mountainous Watershed of Abha, Kingdom of Saudi Arabia. *Environmental Earth Sciences*, *72*(12), 4973-4984. https://doi.org/10.1007/s12665-014-3408-1

Mallick, J., Khan, R. A., Ahmed, M., Alqadhi, S. D., Alsubih, M., Falqi, I., & Hasan, M. A. (2019). Modeling Groundwater Potential Zone in a Semi-Arid Region of Aseer Using Fuzzy-Ahp and Geoinformation Techniques. *Water*, *11*(12), 2656. https://doi.org/10.3390/w11122656

Manap, M. A., Nampak, H., Pradhan, B., Lee, S., Sulaiman, W. N. A., & Ramli, M. F. (2014). Application of Probabilistic-Based Frequency Ratio Model in Groundwater Potential Mapping Using Remote Sensing Data and Gis. *Arabian Journal of Geosciences*, *7*(2), 711-724. https://doi.org/10.1007/s12517-012-0795-z

Moazzam, M. F. U., Rahman, G., Munawar, S., Tariq, A., Safdar, Q., & Lee, B.-G. (2022). Trends of Rainfall Variability and Drought Monitoring Using Standardized Precipitation Index in a Scarcely Gauged Basin of Northern Pakistan. *Water*, *14*(7), 1132. https://doi.org/10.3390/w14071132

Munir, A., Khan, M. B. A. S., Ghufran, M. A., & Fatima, N. (2025). Flood Susceptibility Assessment Using Frequency Ratio Model: A Case Study of District Ghotki and District Kashmore, Sindh, Pakistan. *iRASD Journal of Energy & Environment*, *6*(1), 31-46. https://doi.org/10.52131/jee.2025.0601.0053

Murtaza, G., Valipour, M., Usman, M., Ditta, A., Rizwan, M., Elshamly, A. M. S.,…Munir, A. (2025). Ecological and Health Risk Assessmentof Cadmium Contamination in Groundwatersamples Collected from the Aridclimatic Region. *Polish Journal of Environmental Studies*, *34*(3), 2793-2803. https://doi.org/10.15244/pjoes/188185

Ozdemir, A. (2011). Gis-Based Groundwater Spring Potential Mapping in the Sultan Mountains (Konya, Turkey) Using Frequency Ratio, Weights of Evidence and Logistic Regression Methods and Their Comparison. *Journal of Hydrology*, *411*(3-4), 290-308. https://doi.org/10.1016/j.jhydrol.2011.10.010

Pande, C. B., Moharir, K. N., Panneerselvam, B., Singh, S. K., Elbeltagi, A., Pham, Q. B.,…Rajesh, J. (2021). Delineation of Groundwater Potential Zones for Sustainable Development and Planning Using Analytical Hierarchy Process (Ahp), and Mif Techniques. *Applied Water Science*, *11*(12), 186. https://doi.org/10.1007/s13201-021-01522-1

Pani, S., Chakrabarty, A., & Bhadur, S. (2016). Groundwater Potential Zone Identification by Analytical Hierarchy Process (Ahp) Weighted Overlay in Gis Environment—a Case Study of Jhargram Block, Paschim Medinipur. *Int J Remote Sens Geosci (IJRSG)*, *5*(3), 1-10.

Pourghasemi, H. R., & Beheshtirad, M. (2015). Assessment of a Data-Driven Evidential Belief Function Model and Gis for Groundwater Potential Mapping in the Koohrang Watershed, Iran. *Geocarto International*, *30*(6), 662-685. https://doi.org/10.1080/10106049.2014.966161

Priya, U., Iqbal, M. A., Salam, M. A., Nur-E-Alam, M., Uddin, M. F., Islam, A. R. M. T.,…Rak, A. E. (2022). Sustainable Groundwater Potential Zoning with Integrating Gis, Remote Sensing, and Ahp Model: A Case from North-Central Bangladesh. *Sustainability*, *14*(9), 5640. https://doi.org/10.3390/su14095640

Saaty, T. L. (1994). Highlights and Critical Points in the Theory and Application of the Analytic Hierarchy Process. *European Journal of Operational Research*, *74*(3), 426-447. https://doi.org/10.1016/0377-2217(94)90222-4

Salem, A., Dezső, J., & El-Rawy, M. (2019). Assessment of Groundwater Recharge, Evaporation, and Runoff in the Drava Basin in Hungary with the Wetspass Model. *Hydrology*, *6*(1), 23. https://doi.org/10.3390/hydrology6010023

Saranya, T., & Saravanan, S. (2020). Groundwater Potential Zone Mapping Using Analytical Hierarchy Process (Ahp) and Gis for Kancheepuram District, Tamilnadu, India. *Modeling Earth Systems and Environment*, *6*(2), 1105-1122. https://doi.org/10.1007/s40808-020-00744-7

Senthil Kumar, G., & Shankar, K. (2014). Assessment of Groundwater Potential Zones Using Gis. *Front Geosci*, *2*(1), 1-10.

Shahab, A., Shihua, Q., Rad, S., Keita, S., Khan, M., & Adnan, S. (2019). Groundwater Vulnerability Assessment Using Gis-Based Drastic Method in the Irrigated and Coastal Region of Sindh Province, Pakistan. *Hydrology Research*, *50*(1), 319-338. https://doi.org/10.2166/nh.2018.001

Shahid, S., Nath, S. K., & Roy, J. (2000). Groundwater Potential Modelling in a Soft Rock Area Using a Gis. *International Journal of Remote Sensing*, *21*(9), 1919-1924. https://doi.org/10.1080/014311600209823

Singh, L. K., Jha, M. K., & Chowdary, V. M. (2018). Assessing the Accuracy of Gis-Based Multi-Criteria Decision Analysis Approaches for Mapping Groundwater Potential. *Ecological Indicators*, *91*, 24-37. https://doi.org/10.1016/j.ecolind.2018.03.070

Siva, G., Nasir, N., & Selvakumar, R. (2017). Delineation of Groundwater Potential Zone in Sengipatti for Thanjavur District Using Analytical Hierarchy Process. *IOP Conference Series: Earth and Environmental Science*, *80*, 012063. https://doi.org/10.1088/1755-1315/80/1/012063

Solomon, S., & Quiel, F. (2006). Groundwater Study Using Remote Sensing and Geographic Information Systems (Gis) in the Central Highlands of Eritrea. *Hydrogeology Journal*, *14*(6), 1029-1041. https://doi.org/10.1007/s10040-006-0096-2

Xiang, Z., Bailey, R. T., Nozari, S., Husain, Z., Kisekka, I., Sharda, V., & Gowda, P. (2020). Dssat-Modflow: A New Modeling Framework for Exploring Groundwater Conservation Strategies in Irrigated Areas. *Agricultural Water Management*, *232*, 106033. https://doi.org/10.1016/j.agwat.2020.106033

Zhao, W., Ma, J., Gu, C., Qi, S., Zhu, G., & He, J. (2016). Distribution of Isotopes and Chemicals in Precipitation in Shule River Basin, Northwestern China: An Implication for Water Cycle and Groundwater Recharge. *Journal of Arid Land*, *8*(6), 973-985. https://doi.org/10.1007/s40333-016-0091-y