Assessment of Groundwater Potential Zones Using Electrical Resistivity in Muzaffargarh

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The study integrates Earth observation and geospatial data to assess groundwater potential and conditions in Muzaffargarh, South Punjab, Pakistan. The region faces freshwater scarcity due to high sediment concentration in subsurface water. The approach developed will offer significant potential for sustainable water resource management in regions affected by high sediment concentrations in subsurface water. An electrical resistivity survey was conducted at 40 locations within the study area. Vertical Electrical Sounding (VES) and spatial analysis were integrated with hydrogeological parameters to analyze and visualize the spatial patterns of freshwater availability. A weighted overlay with relative contribution was applied to map the fresh and saline water zones, aided by 2D resistivity maps. Several thematic layers were generated using data on geology, rainfall, lineaments, land use/land cover (LULC), drainage density, soil type, and slope. A groundwater potential (GWP) zone map was then created, categorizing the study area into four zones: very good, good, moderate, and poor. Additionally, resistivity maps were generated at depths of 2m, 10m, 50m, 80m, 200m, and 300m to analyze the variation in resistivity values in the Ghazi Ghat and Qasba Gujrat areas of Muzaffargarh district. The study's outcomes included curves indicating the application of potential groundwater zones in the study area and similar regions. The different resistivity curves generated, and their subsequent comparison provided a comprehensive understanding of the subsurface characteristics. These findings offer valuable insights for the sustainable management of groundwater resources in the region, particularly in addressing freshwater scarcity issues.

Keywords: Electrical Resistivity Survey, Vertical Electrical Sounding, Google Earth Engine, Groundwater Potential Zone.

Introduction:

A region's socioeconomic development and urbanization are significantly influenced by its sustainable freshwater supply [1]. Water could dissolve, suspend, soak, and adsorb a wide range of pollutants, including organic and inorganic substances like arsenic, sulfides, and chlorides, due to the high solubility of diverse solutes in it [2]. Pakistan is one of the nations that is experiencing a shortage of freshwater. Most of the nation is located in arid to semi-arid areas with little precipitation. Most people rely on groundwater for their industrial, agricultural, and domestic requirements. Poor solid waste disposal practices are the primary cause of groundwater contamination, whereas excessive groundwater extraction is one of the key factors contributing to the rising salinity of the groundwater [3]. One of the most precious natural resources is groundwater, which promotes biological diversity, economic growth, and human health. Subsurface water that fills pore spaces in soil and fractures in rock formations is known as groundwater. It is recognized as a substitute source of water for all organisms. Groundwater occurrence and its movement in an area depends on various aspects. Throughout the hydrological cycle, waters interact with different agents and go through various phases. This whole process takes place in an equilibrium manner, i.e., the total inflow is equal to the outflow in that system and the net change in total quantity is negligible or zero [4][5]. The world's water resources are dispersed randomly. Therefore, effective scientific methods are needed to identify possible aquifer zones for replenishment and utilization. Geophysical science uses measurements made at or close to the earth's surface to investigate the planet [6]. One of the geophysical techniques utilized as an initial step in any groundwater research is the Electrical Resistivity Method (ERM). For many years, ERM has been used to map the geological environment of the current aquifer and assess the thickness of layered media. Because of its ease of use, effectiveness, and non-destructiveness in generating subsurface imaging when compared to traditional methods, it has been successfully applied to groundwater. Groundwater potential zonation is the process of assessing an area's groundwater zones' potentiality using both quantitative and qualitative methods, employing surface and subsurface indicators either directly or indirectly. While subsurface data can be gathered using observatory wells, electrical resistivity techniques, and direct observations in potential exposures, surface features can be readily accessed through remote sensing and field verification. An indirect way to interpret the subsurface geological conditions, particularly in the lineaments and worn rock zones, is the electrical resistivity sounding method. Since vertical electrical sounding is better and appropriate for deep probing and is less expensive, it is one of the most widely used and dependable techniques.

The application of remote sensing, Geographic Information Systems (GIS), and electrical resistivity has revolutionized the way we assess and manage freshwater resources. In an era where the demand for clean and sustainable groundwater sources is escalating, these technologies have become indispensable tools for locating and characterizing potential groundwater zones. Combined with GIS, it enables the integration, analysis, and visualization of spatial data, facilitating a comprehensive understanding of the subsurface environment. Electrical resistivity, on the other hand, allows us to directly probe the geological formations beneath the surface, gauging their capacity to store and transmit groundwater. This integrated approach has the potential to identify, delineate, and assess freshwater potential zones with a high degree of accuracy, aiding in the sustainable management of this vital resource. In this exploration, we delve into the intricate synergy between these technologies and their pivotal role in safeguarding our freshwater supply.

This study aimed to assess and delineate fresh groundwater potential zones using a combination of remote sensing, GIS, and electrical resistivity methods. One of the main goals of groundwater research and management is to distinguish between the interfaces of fresh and salt water. The proposed research will contribute to the sustainable utilization of groundwater resources and the delineation of saline and freshwater layers within the subsurface. Various conventional methods, such as geological and geophysical methods, are applicable to confirm the presence and measure the appreciable quantity of groundwater in an area. However, compared to these methods, remote sensing can be used as a tool which is much more effective in a way that it is more convenient, time-saving and cost-effective tool for the reconnaissance survey [7][8][9]. As a tool, remote sensing and GIS utilize satellite imageries, digital elevation models, conventional maps and field-generated data for the generation of thematic maps of Land Use and Land Cover (LULC), drainage network, drainage density, slope of the area, geology, geomorphology, rainfall distribution, groundwater level and lineament density. The electrical resistivity sounding method is an indirect method of interpreting the subsurface geological conditions especially the lineaments and weathered rock zones [6]. Vertical electrical sounding (VES)is one of the most widespread and reliable techniques as it is inexpensive and more suitable for depth probing [10][11][12]. Other than groundwater exploration and understanding sub-surface lithology, studies can also be carried out on aquifer parameters and their characteristics using VES data [13][14]. The hydraulic and geoelectric parameters of an aquifer and their relationship are controlled by the composition and subsurface lithology of the aquifers [15]. Delineation of Ground Water Potential Zone (GWPZ) can be done using VES data [16][17].

The main objective of this research is to assess groundwater potential zones in Muzaffargarh, South Punjab, Pakistan, by integrating Earth observation and geospatial data analysis. This study aims to address the region's freshwater scarcity, which is caused by high sediment concentrations in subsurface water. By developing an approach for sustainable water resource management, the research seeks to provide significant benefits to areas affected by similar conditions. For this, an electrical resistivity survey was conducted at 40 locations within the study area. The Vertical Electrical Sounding (VES) and spatial analysis were integrated with hydrogeological parameters to analyze and visualize the spatial patterns of freshwater availability. A weighted overlay with relative contribution was applied to map fresh and saline water zones using 2D resistivity maps. The study also aims to determine the depth and quality of water at various levels, recognize freshwater zones in the subsurface, and create a comprehensive groundwater potential map by integrating remote sensing, GIS, and electrical resistivity data.

Material and Methods:

Description of Study Area

Muzaffargarh is an agricultural district in Punjab. It lies between 29° 6' to 30° 45' N latitude and 70° 30' to 71° 48' E longitude, centrally located in Pakistan between the renowned Chenab and Indus rivers. The district comprises four tehsils: Alipur, Jatoi, Kot Addu, and Muzaffargarh. It has a total of 1,084 km of metalloid roads, connecting the district to Multan, Rajanpur, D.G. Khan, and Rahim Yar Khan districts. The district of Muzaffargarh covers a total area of 830 thousand hectares. Out of this, 112.7 thousand hectares are affected by salt, and 1.17 thousand hectares are waterlogged. According to the 1998 census, the population of the district in Pakistan was 2,635,903 inhabitants. [18]. Thal Doab is a triangular-shaped region, which is bounded by the Indus River on the Westside, and by the river Chenab on the East. Thal Doab covers an area of 7.9 million acres [19][20]. Our study area is a part of Thal Doab in the district of Muzaffargarh the average elevation of the study area is around 122m from the mean sea level and lies along the southern bank of the Chenab River [21]. The hydrology of the area presents several pressing issues that require resolution, notably water scarcity and contamination. Locals have long faced water shortages, and the quality of available water is a significant concern due to contamination. Numerous surveys have been conducted to address these challenges. In the study area, a primary issue is the lack of clean water, leading to various health issues among residents. Muzaffargarh, located in the arid region of Punjab, experiences minimal yearly rainfall, exacerbating problems such as soil salinity. A key objective of the study is to identify significant freshwater aquifers and areas where subsurface water is contaminated.

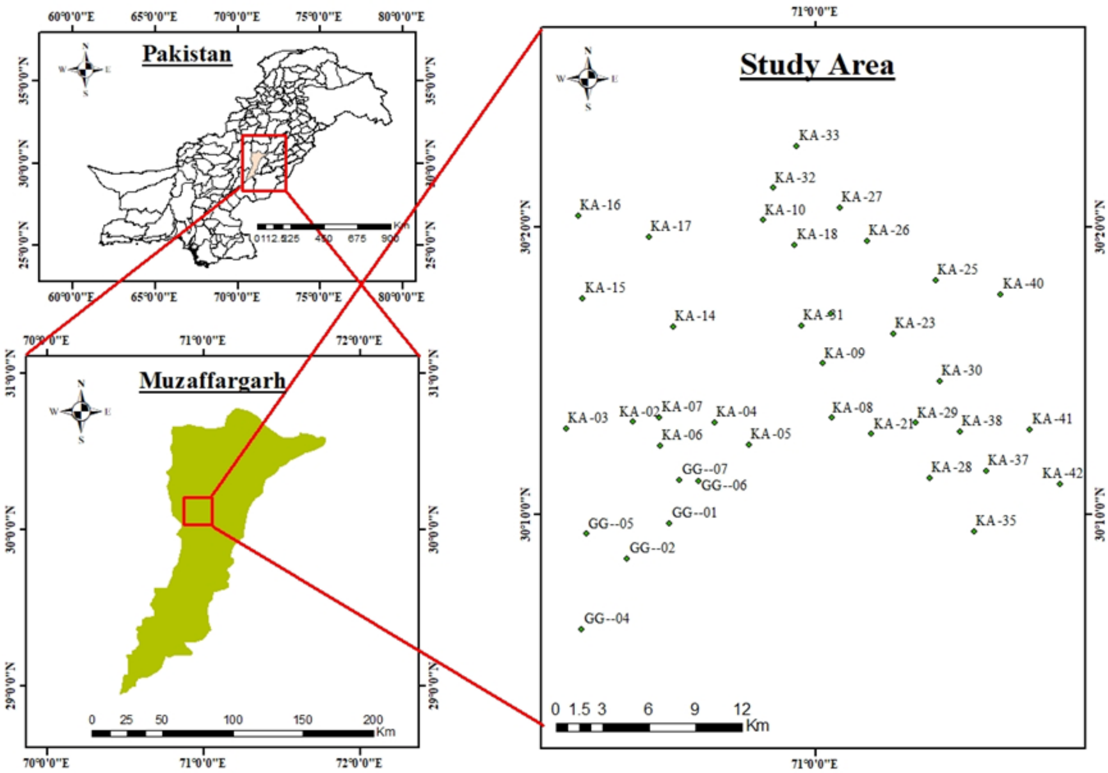


Figure 1: Map showing the location of the study area and distribution of ground survey points in southern Punjab Pakistan

Geology of Muzaffargarh:

The district Muzaffargarh is divided into several lithological units using a published geological map from the Geological Survey of Pakistan (GSP, 1964) compiled by M. Abu Bakr, M.S.C., Geological Survey of Pakistan, and Roy O. Jackson, U.S. Geological Survey. The research region is part of the Central Indus Basin. The whole research area (Muzaffargarh) is comprised of quaternary deposits which are further classified as: Eolian sand of Thar desert OR Dune sand deposits (Qs), Flood plain deposits OR Eolian sand deposits, deposits of extinct streams having relief less than 100ft (Qsc), Stream-bed and Meander-Belt deposits (Qm), Active floodplain deposits (Qf).

Data Collection:

An electrical resistivity survey used for water quality estimation of Thal desert. Thal desert area mainly consists of clay, sand, silt, silty clay, etc. Among three types of configurations, Schlumberger configuration was used in the study area. In which electrodes were joined in a straight line to form a circuit and distance among inner electrode was same but outer electrode distance was changed at every VES point. Schlumberger configuration means that the current electrode spacing should be greater or equal to the inner electrode distance. There are some conditions that must be fulfilled before starting a resistivity survey.

$$AB \geq 5MN \qquad (1)$$

- Resistivity contrast should be present among the formations under examination.
- If the surface consists of thinner alternate layers the measured resistivity is the average effect of these layers.
- Resistivity array should be away from electrical lines in the field but if lines are near to the point of investigation, then the array should be perpendicular to these electrical lines so that electrical lines do not add up in resistivity value and make it noisy.

By using Schlumberger configuration almost 40 VES points were made. At every VES point, the AB/2 distance was 1.5, 2, 3, 4,6, 8, 10, 15, 20,25, 30, 40, 50, 60, 80, 100, 125, 150, 200, 250, 300 meters. AB/2 distance was changed at every VES point and when the Schlumberger configuration started giving low resistivity values the MN distance was also changed. When the circuit was completed, a current of 200ma was inserted in the ground and then this current gave the potential in potential electrodes which were calculated. At different spacing earth offers resistance, to calculate that resistivity a resistivity meter was used. Resistance was measured in ohmmeters. Our focus for this survey was to calculate apparent resistivity. Apparent resistivity is the average resistivity of subsurface materials. For the calculation of apparent resistivity, we need resistance and a geometric constant K and both of these were calculated from field measurements.

$$\rho_a = R*K \qquad (2)$$

- ρ_a = apparent resistivity
- K= geometric constant
- R = resistance offered by ground
- R is calculated by using the given formula

$$R = \frac{V}{I} \qquad (3)$$

- R = resistance
- V = Potential difference
- I = electric current

Geometric factor K was calculated by using the given formula

$$K = \pi * \frac{(AB/2)^\wedge 2 - (MN/2)^\wedge 2}{MN} \qquad (4)$$

- AB = distance between outer current electrodes
- MN = distance between inner potential electrodes

Apparent resistivity was calculated by using the above formulas and then values for all these parameters calculated to make graphs for apparent resistivity. Graphs were plotted between AB/2 and apparent resistivity, AB/2 taken on x-axis while ρ_a on the y-axis. After making graphs for each VES point and making a Word file of it, the data is further processed in the software IPI2WIN. This software is used to make synthetic curves corresponding to the field resistivity curves. Field resistivity curves formed with the help of data which is acquired on the field and synthetic ones were made by minimizing all the possible errors.

Models generated by IPI2WIN were then used to find the number of layers thickness and depth of these layers. The table window that appears along with the curve window also shows the Root Mean Square error. This error should be less than 1% so to reduce this error value of apparent resistivity was changed, to proceed with the processing we changed ρ_a (apparent resistivity) by changing this, the RMS value also continued to change. However, some of the models created by IPI2WIN are given in Figure 6. In these models the red curves represent synthetic curves or best fitted curves and the black curves are field data curves. Blue layers are the layers of lithological units. Identification of layers is achieved by analyzing the values of these curves. VES is a reliable non-destructive method used for groundwater exploration. It requires specific conditions to be met and can be further validated by correlating the results with borehole data. Although this data acquisition method is highly reliable and useful, it has a limitation: it requires a long array of wires, which can be difficult to manage when collecting data from deep resources. Despite this drawback, the method's reliability makes this limitation less significant.

$$CR = \frac{CI}{RI} \qquad (5)$$

Where RI = random index, CI = consistency index, CR= consistency ratio. If CR value ≤ 0.10, it is acceptable and If CR = 0, it is the perfect level. The district of Muzaffargarh freshwater or groundwater potential zone map was created by combining all seven thematic maps using the weighted overlay assessment approach on a GIS platform and using an algorithm.

Research Methodology:

In this study, various spatial analysis techniques in ArcGIS were employed to process and evaluate integrated datasets, including the creation of derivative maps and conducting spatial overlays to identify relationships and patterns among variables (Figure 2).

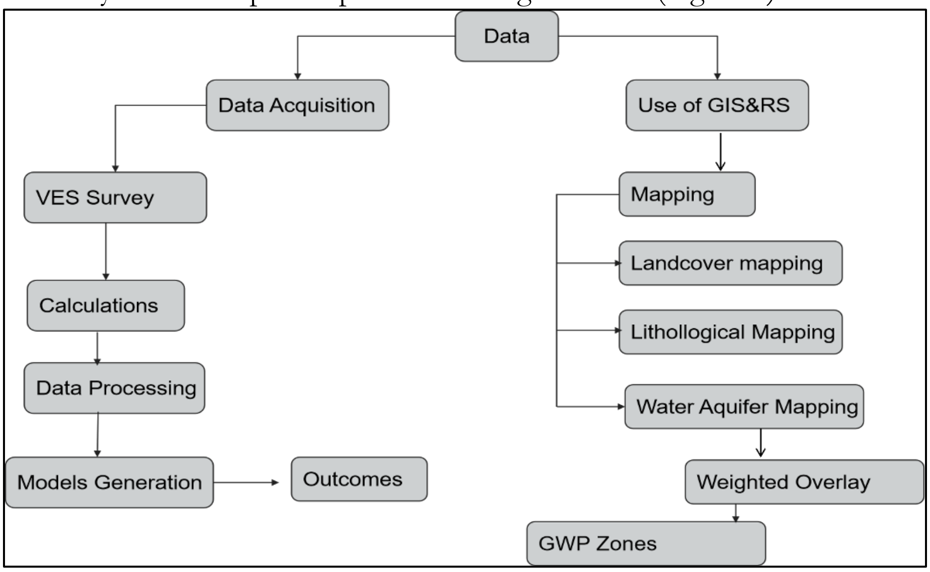


Figure 2: Flow chart indicating the step-by-step procedure adopted in the study

Remote sensing GIS methods were utilized for hydrologic investigations of drainage basins, encompassing a range of activities relevant to the physical environment of the drainage basin and surrounding areas. These investigations are particularly important in dry regions facing challenges such as the unavailability of freshwater resources and the prevalence of flash floods. RS and GIS were used to extract hydrological data for further analyses, with a focus on qualitative and quantitative assessments of drainage system parameters in dryland environments.

The study utilized various geospatial data sets including the DEM from the Shuttle Radar Topography Mission (SRTM) downloaded from USGS website and field surveys, soil types, water table depth, and geological data. These datasets were processed in ArcGIS version 10.5 to analyze various factors such as DEM, land use, soil types, geomorphology, hillshade, and drainage density. Thematic maps including geology, drainage density, soil, land use/land cover (LULC), rainfall, lineament density, and slope maps were prepared to calculate and estimate recharge potential and groundwater potential zones in the study area. Soil map was prepared from the data downloaded from website name "soilgrid". LULC data was directly downloaded from ESRI website while rainfall map was prepared by the data downloaded from a website named "crudata". Geology map was digitized using the map made by Geological Survey of Pakistan. Other maps were prepared by using DEM data.

Additionally, the study aims to use data from Electrical Resistivity Surveys conducted in the field to determine subsurface layers using the Inverse Slope method with IPI2WIN software. Satellite data was also utilized for map creation. For groundwater investigation, different techniques are in practice [22]. Electrical resistivity survey is one of the geophysical methods, widely used for groundwater prospecting and hydrogeological investigations of the subsurface. This technique is useful where resistivity contrast present among surrounding formation and water-bearing strata. Electrical resistivity method is used to resolve thickness and resistivities of layered medium for investigation of groundwater and boreholes. This is an effective tool for locating groundwater aquifers. VES is a liable technique that is used for the detection of groundwater, depth to bedrock, etc. This technique uses four electrodes two of them are current electrodes and the other two are potential electrodes. These four electrodes are positioned and connected to measure values. Current electrodes are used to insert current in the ground and potential electrodes measure the potential difference. The current electrodes called A and B while the potential ones named M and N electrodes. The four electrodes were connected to a Terameter with the assistance of wires. The current electrodes insert the current in the ground and their resulted potential is calculated. This array of electrodes is known as Schlumberger electrode configuration which is illustrated in figure. 3.

Table 1: AHP matrix indicating weight for each layer

Matrix		Rainfall	Geology	Slope	Drainage Density	LULC	Lineament Density	Soil	**Normalized Principal Eigenvector**
		1	2	3	4	5	6	7	
Rainfall	1	1	2	1	5	1	3	6	25.38%
Geology	2	1/2	1	1	5	2	2	6	21.79%
Slope	3	1	1	1	2	1	1	4	15.70%
Drainage Density	4	1/5	1/5	1/2	1	1	2	3	9.19%
LULC	5	1	1/2	1	1	1	3	6	16.16%
Lineament Density	6	1/3	1/2	1	1/2	1/3	1	4	8.75%
Soil	7	1/6	1/6	1/4	1/3	1/6	1/4	1	3.02%

The weighted overlay method in ArcGIS 10.5 used to overlay various maps to estimate the groundwater zones. Each layer has a weight and rank, as shown by Equation (6). Where A is the weight of parameter while B is the rank of subclasses present in map of each parameter and i is initial and n is the last value or number of parameters. The groundwater potential zone was delineated by combining all of the thematic layers using the raster calculator in ArcGIS 10.8 software after the total normalized weights of each theme layer and its associated attributes were established. Based on the groundwater potential zone's cumulative score, four classes were determined: very good, good, moderate, poor.

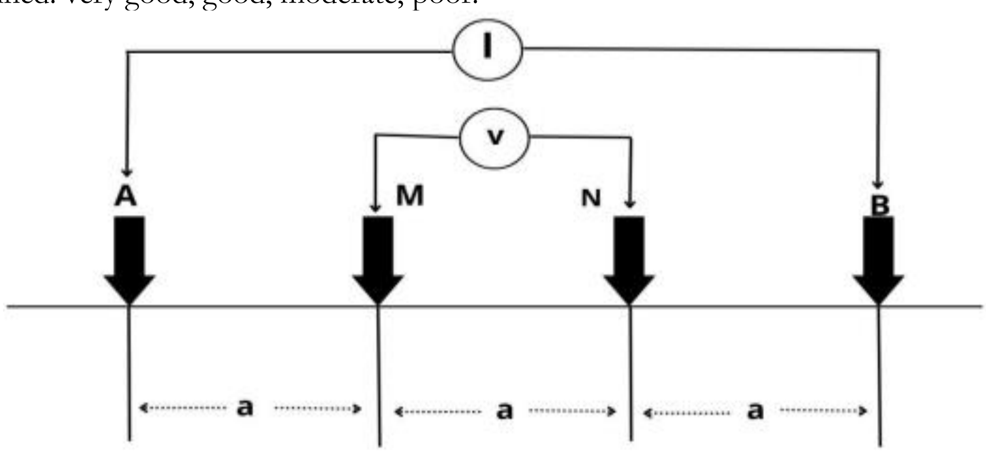


Figure 3: Illustration of electrode array using Schlumberger electrode configuration used in field during data acquisition.

Results:

The research region lies within the Central Indus Basin, specifically in Muzaffargarh, which is characterized by Quaternary deposits. By using arc GIS different layers were created. Details of these layers are given in Figure 4. By using ground data and IPI2WIN different models were generated which depict the subsurface lithologies and the type of water present beneath the subsurface. All of this is determined with the help of resistivity values. Low resistivity values are indicative of clay sediments if above the water table and of saline water below the water table. Whereas high resistivity values indicate the presence of fresh water with some sandy strata. The resistivity values of materials given in Table 2 are used in this research. With the help of ground data acquired in the field, it is then plotted in ArcGIS to map resistivity at different depths which is shown in Figure 7.

Table 2: Resistivity threshold values for various lithologies utilized in the interpretation of Vertical Electrical Sounding (VES) data.

Resistivity Zone	Resistivity Range (ohm-m)	Interpreted Lithology
Very high	Greater than 230	Coarse sand with gravels and Kanker
High	230 to 100	Sand with gravels with minor interbedded thin layers of silt and clay
Medium	100 to 40	Medium to coarse sand
Low	40 to 20	A mixture of sand with silt and clay
Very low	Less than 20	Silty clay / clayey silt (Above GWT) Saline sediments, silty clay in dominance (Below GWT)

Elevation and Slope:

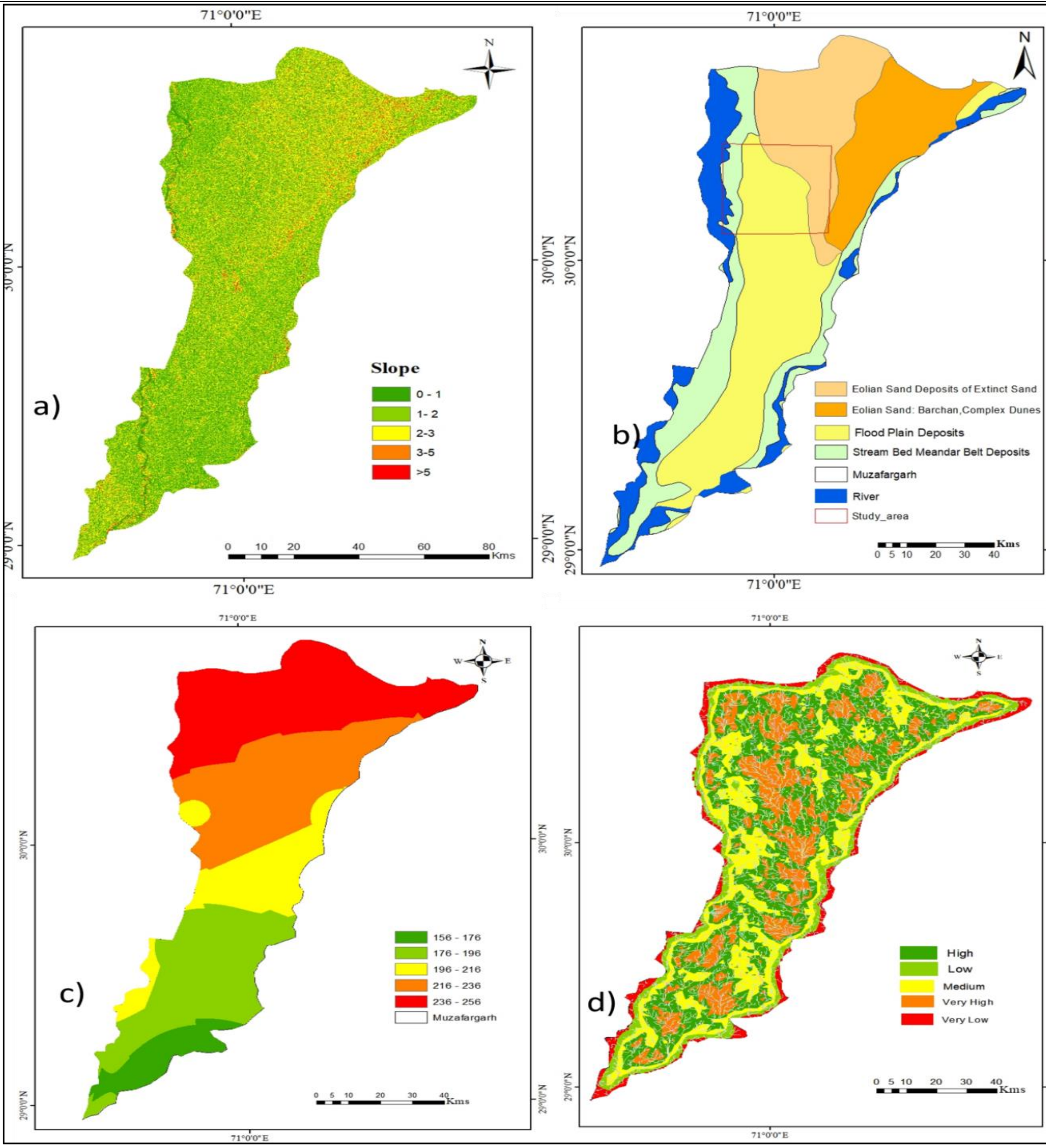
The elevation of the land surface significantly influences groundwater replenishment, primarily by driving water movement through gravity. By analyzing elevations, we can determine the regions that contribute to groundwater flow [23]. Elevation is a topographic feature useful for investigating groundwater potential. The elevation map of the study area has been developed using the SRTM DEM. Climate variations are influenced by altitude, affecting rainfall patterns and soil quality [24]. Elevation gradients impact groundwater direction and flow, while landscape elevation changes contribute to groundwater recharge and movement. This information is crucial for effective water resource management and sustainability [25]. Generally, flat land surfaces exhibit lower runoff compared to moderately and highly elevated areas. Runoff in flat areas ranges from 0 to 0.4%. Infiltration is greater in regions with a flat slope than in those with a steep or moderately steep slope.

Soil Texture:

Land water infiltrates through the voids in the soil to reach the aquifer. Soil is a fundamental factor in determining potential groundwater zones. Therefore, various technologies and techniques, such as remote sensing, GIS, and AHP, are employed in groundwater research [26]. Soil type maps are created using the average size of solid particles in the soil, such as sand, silt, and clay. Soils with high infiltration rates, like sand, gravel, and boulders, are assigned higher weights (Figure. 4g).

LULC:

Land Use and Land Cover (LULC) maps were generated by classifying raster data sets for the years 2000, 2010, and 2020, as illustrated in Figure. 4, f). Seven categories were created based on land use types for these different years.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b)
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Flood Plain Deposits
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0 5 10 20 30 40
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c)
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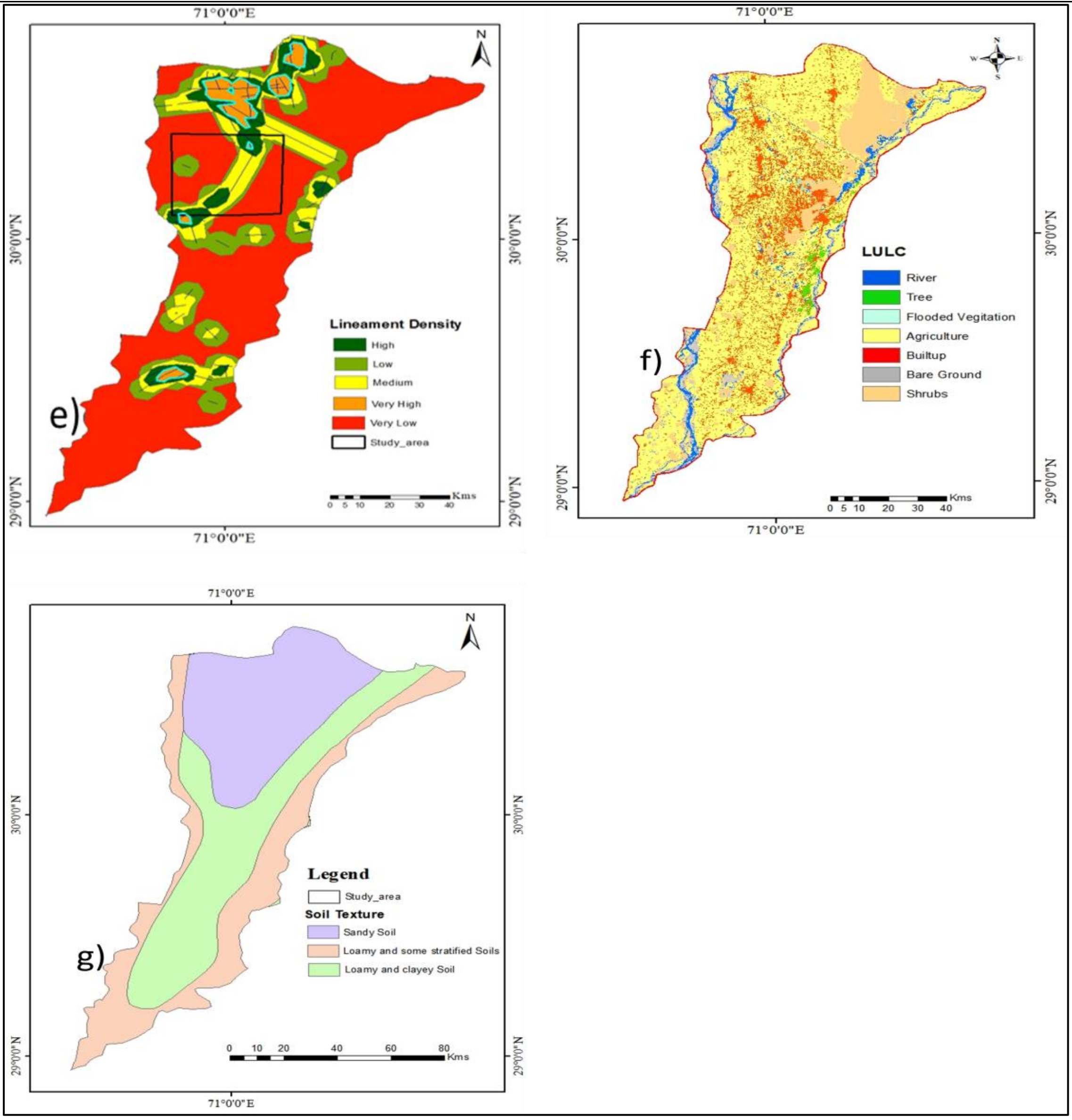

Figure 4: The map of thematic layers for Muzaffargarh, utilized in creating the GWPZ map, includes the study area indicated by a small black box. This figure comprises the following: a) Slope, b) Geology, c) Rainfall, d) Drainage Density, e) Lineament Density, f) Land Use/Land Cover (LULC), and g) Soil Classification Map.

Rainfall:

Rainfall data was downloaded for year 2011-2021 and then processed in arc map for making average rainfall map which is given in Figure. 4, c). The essence of geophysical methods lies in analyzing the subsurface geology of a specific area of interest. These methods utilize devices to detect discontinuities caused by contrasts in the physical properties of rocks. Due to the complexity of geophysical patterns and the interpretation of these discontinuities, it is common to use an integrated survey, combining two or more geophysical methods. This approach helps to reveal the subsurface geology more accurately and mitigates issues caused by the earth's inhomogeneous nature. In this project, a geophysical survey was employed, incorporating GIS&RS and electrical resistivity methods for Groundwater exploration.

Groundwater Potential Zone Map: A GWP zone map was created using thematic layers. The study area categorized into four zones i.e. very good, good, moderate, poor etc. This given in Figure 5.

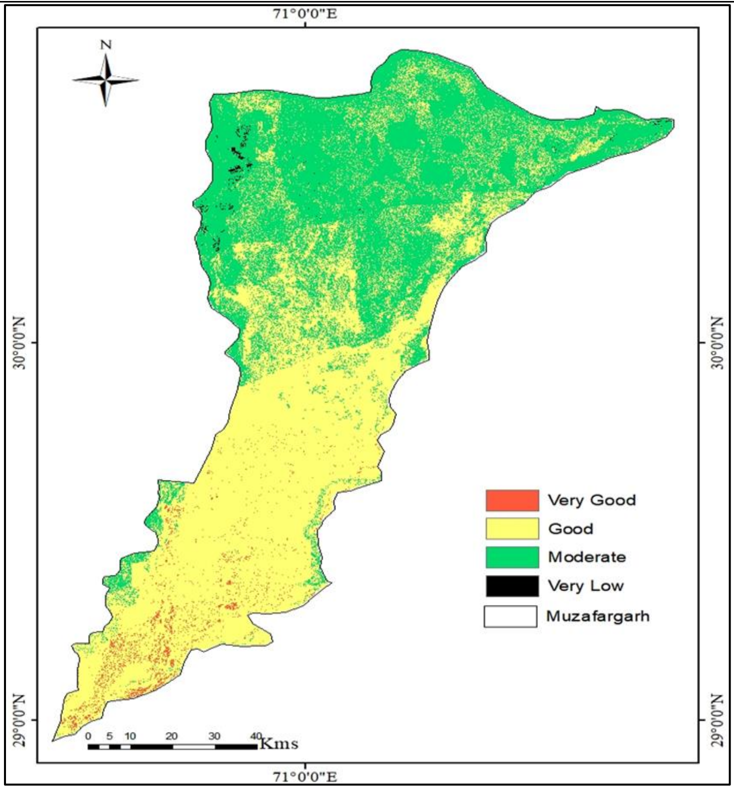

Figure 5: Groundwater Potential Zone Map of Muzaffargarh, it classifies the area into four groundwater quality zones: Very Good, Good, Moderate, and Very Low.

Interpretation of some of points is given below:

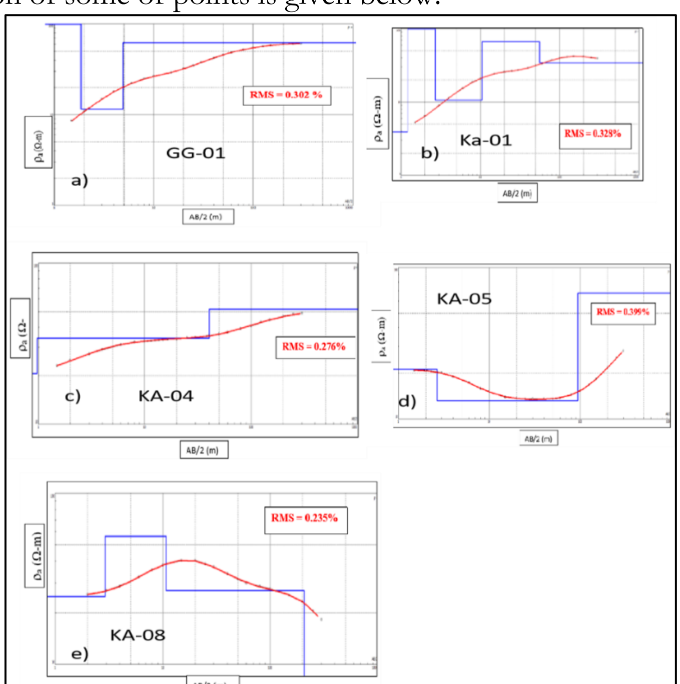

Figure 6: 1D inverted models of apparent resistivity data are indicated by small circles. The solid black curve represents the apparent resistivity curve, while the red curve is the best fit to this data. The solid blue block line shows the modeled (synthetic) resistivity. The horizontal axis represents the current electrode spacing (AB/2) in meters, and the vertical axis shows the resistivity in ohm meters. The figure includes the following plots: a) GG-01, b) KA-01, c) KA-04, d) KA-05, and e) KA-08.

Table 3: Interpretation of GG-01

Layer No.	Resistivity (Ohm-m)	Thickness (m)	Depth (m)	Interpretation	Remarks
1	3.91	1.21	1.21	Clay	The third, fourth, and fifth layers are water-bearing. Drilling is required for further investigation.
2	191	1.48	2.69	Gravel	
3	10.6	7.82	10.5	Saline sediments	
4	66.6	45.7	56.2	Medium to coarse grain sand with fresh groundwater	

Table 4: Interpretation of KA-04

Layer No.	Resistivity (Ohm-m)	Thickness (m)	Depth (m)	Interpretation	Remarks
1	20.6	0.964	0.964	Clay or silt	The second and third layers are water-bearing. Drilling is required for further investigation
2	34.3	39.2	40.1	Clay or silty clay or clayey silt saturated with water	
3	51.6			Medium to coarse grain sand with fresh groundwater	

Table 5: Interpretation of KA-05

Layer No.	Resistivity (Ohm-m)	Thickness (m)	Depth (m)	Interpretation	Remarks
1	21.2	2.66	2.66	Clay or silt	The second and third layers are water-bearing. Drilling is required further.
2	13.2	92.2	94.9	Saline sediments	
3	67.9			Medium to coarse grain sand with fresh groundwater	

Table 6: Interpretation of KA-08

Layer No.	Resistivity (Ohm-m)	Thickness (m)	Depth (m)	Interpretation	Remarks
1	25	2.9	2.9	Clay or silt	
2	55.8	7.87	10.8	Medium to coarse grain sand with fresh groundwater	The second, third, and fourth layers are water-bearing. Drilling is required for further
3	27	198	209	Clay or silt with marginal water	
4	0.354			Saline sediments	

Resistivity maps were generated at depth levels of 2m, 10 m, 50 m, 80 m, , 150 m, 200 m and 300 m to analyze the variation of resistivity values in the Ghazi Ghat and Qasba Gujrat areas of the Muzaffargarh district. Clays to silty clay sediments and surface materials, which are present above the water table, exhibit low resistivity values. Water-soaked sand sediments are associated with a resistivity range of 40-100 ohmmeters. Saline sediments display low resistivity values both above and below the water table. However, resistivity maps based on ground data at various depths have been created to illustrate the quality of groundwater at different locations. These maps also clearly show the variations in resistivity and water quality according to depth. These maps given in Figure 7.

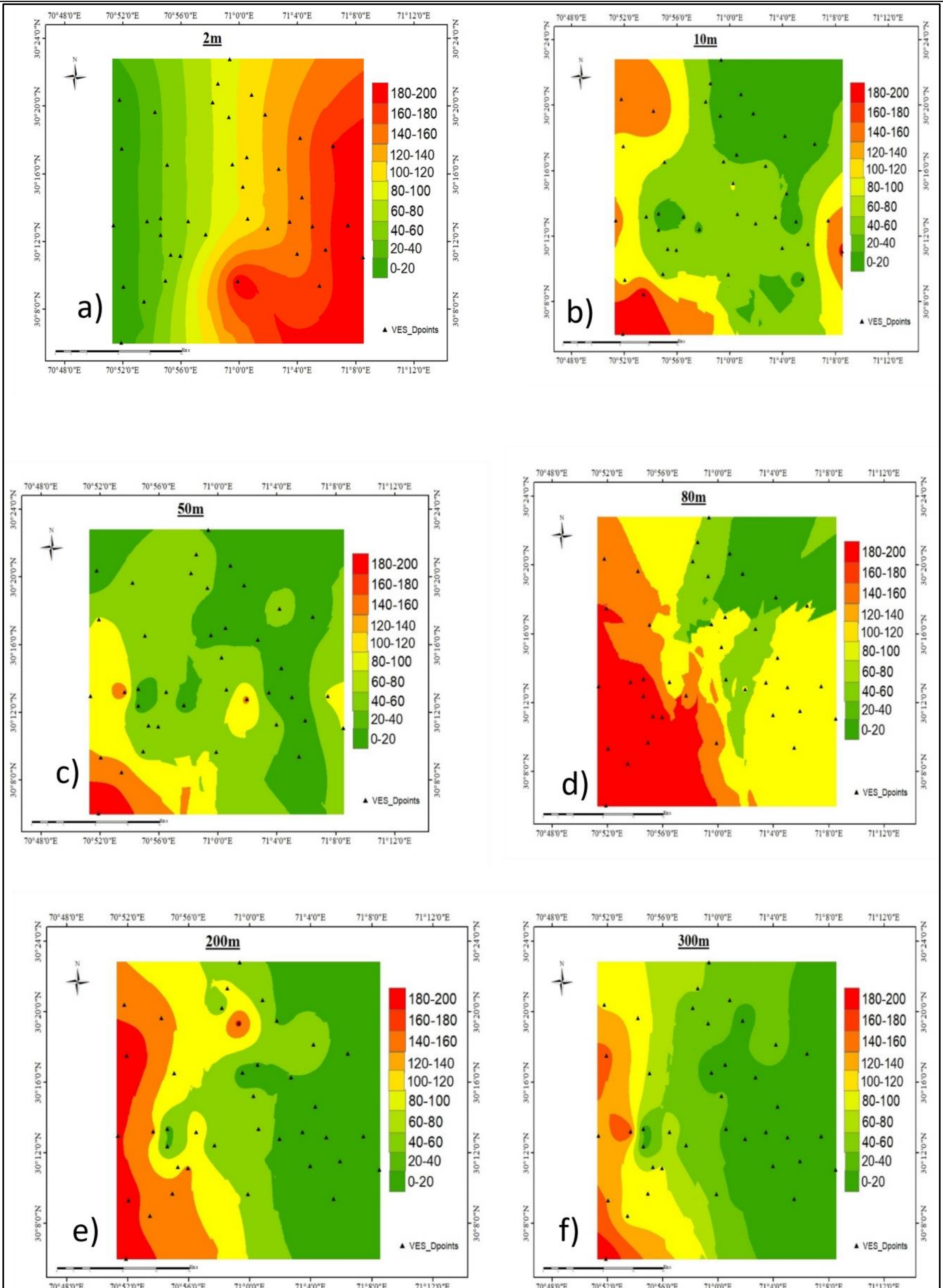

Figure 7: Contour map representing resistivity distribution at study area in Muzaffargarh at different depth i.e. a) 2m, b) 10m, c) 50m, d) 80m, e) 200m, f) 300m

Discussion:

Several studies have highlighted the risks linked to the depletion of groundwater due to its use in agriculture. In the current study, almost 40 different location observations of groundwater levels have been carried out in the field for resistivity modelling and making groundwater maps. Resistivity models are generated and plotted, displaying resistivity values against depths. These models consist of sequences of horizontal layers, distinguished by discrete bands of resistivity. General calibration between lithology and resistivity is established using the provided information and resistivity data. Table (2) represents general resistivities and their corresponding lithologies.

Interpreting the VES results in this region was difficult because the resistivity readings between the shallow and deep alluvium were quite similar. Sand and gravel sediments make for good aquifers for fresh groundwater, while clay-rich sediments function as aquifers for saline water**.** In Figure 6, the red curves represent synthetic or best-fit curves for the field data. These models demonstrate a Root Mean Square Error (RMSE) that should be less than 1. The synthetic curves are used to minimize this error. The blue line in the figure depicts the subsurface lithologies along with their corresponding depths. Figure 6a illustrates four subsurface layers: clay, gravelly sand, silt, and sand saturated with freshwater. Low resistivity values suggest the presence of saline water, whereas high resistivity values indicate freshwater beneath the subsurface. Figure 6 b) illustrates five geo-electric layers, each characterized by distinct lithologies: clay, gravel, saline sediments, medium to coarse-grained sand containing freshwater, and water-saturated clay or silty clay. These layers are located at the coordinates 30º 18′ 94″ N, 70º 94′ 97″ E.

Figure 6 c) is located at 30º 13′ 11″ and longitude 70º 56′ 28″, where the water table is 4-5 meters below the surface. It shows three lithologic layers: the top layer is composed of clay or silt, the middle layer consists of clay or silty clay saturated with water, and the bottom layer is made up of medium to coarse-grained sand saturated with freshwater. Figure 6 d) is situated at coordinates 30º 12′25″N, 70º 57′ 40″E, with a water table depth of 4-5 meters. It comprises three lithologic units. The uppermost layer is composed of clay or silt, the second layer contains saline sediments, and the third layer consists of medium to coarse-grained sand with fresh groundwater. Figure 6 e) is located at coordinates 30º 13′ 21″ N, 71º 00′ 33″ E, with a water table depth ranging from 3 to 5 meters. It comprises four lithologic units. The uppermost layer consists of clay or silt. The second layer contains medium to coarse-grained sand with fresh groundwater. The third layer is composed of clay or silt, while the fourth and final layer consists of saline sediments.

In the study area, resistivity values are categorized as follows: very high (greater than 230 Ω-m), high (between 100 and 200 Ω-m), medium (between 40 and 100 Ω-m), low (between 20 and 40 Ω-m), and very low (less than 20 Ω-m). The electrical resistivity data indicates the presence of thick layers of Quaternary sediments in the subsurface, primarily composed of clay, silt, sand, and gravel. These resistivity values were determined from data prepared in the field and plotted at various depths in ArcGIS. To analyze the variation in resistivity values in Muzaffargarh, various resistivity maps are created at different depths, both above and below the water table. These maps are presented in Figure 7 at depths of 2m, 10m, 50m, 80m,200m ,300m. The chosen depth levels result from a thorough analysis of the resistivity data to pinpoint areas with the greatest resistivity fluctuations. Figure 7a illustrates the resistivity map at a depth of 2 meters, which lies above the water table. Consequently, the resistivity values primarily indicate lithologic variations. In the research area, the resistivity values range from less than 10 Ω.m to over 250 Ω.m, as depicted in Figure 7a.

At a depth of 2 meters, the sampling locations towards the west exhibit low resistivity values, suggesting the presence of alluvium or silty materials. In contrast, the sampling locations towards the east display high resistivity values, indicating the presence of boulders, gravelly, or sandy strata which is not saturated, as the water table is below this depth. Figure 7b shows the variation of resistivity at a depth of 10 meters. In some areas, resistivity ranges from medium to high, and in these locations, the groundwater table is above 10 meters, so high resistivity values indicate the presence of freshwater. Resistivity values up to 40 Ω.m. suggest silty clay or clayey silt with brackish or slightly good quality ground water, while values < 10 Ω.m. below the water table show saline sediments. Sand-gravel with good groundwater is indicated by resistivity values greater than 40 Ω.m. The resistivity values help determine whether the strata are saturated with saline water or freshwater.

Figure 7 c) represents the resistivity distribution at 50m and only three to four locations are indicative of high to very high resistivity values ranging from 120-200 Ω.m.. these values indicate the presence of freshwater while other location indicates values ranging from low to medium resistivity. Figure 7 d) represents resistivity distribution at 80m depth and this map shows a trend of low to high resistivity from east to west. In Figure 7 e) & f) only few locations are favorable for presence of freshwater towards west. This region contains sand and gravel with fresh and saline water. The type of sediments is also determined using resistivity values. The resistivity analysis of this research area reveals that the freshwater aquifer present on the western side of study area, which has a slight salt content, is primarily influenced by a paleochannel with dissolved salts. During the alluvial and fluvial deposition of sediments from volcanic rocks and ash in the surrounding region, the salt content infiltrated the aquifer.

Conclusion:

In the present study, the effective use of techniques such as Remote Sensing (RS), Geographic Information Systems (GIS), the Analytical Hierarchy Process (AHP), and electrical resistivity facilitated the evaluation and identification of potential groundwater zones. The study followed several steps, beginning with the development of thematic layers, assigning weights to each influencing factor using the AHP method, and concluding with overlay analysis to demarcate groundwater potential zones. Additionally, electrical resistivity surveys were conducted to investigate groundwater conditions.

The subsurface resistivity data collected during the survey were processed using IPI2WIN software, revealing three to five geoelectric layers in the study area. These layers consisted of organic content, silty clay, fine to coarse sand, and gravel at certain profiles.

The low resistivity values indicate the presence of surface material with saline water. In contrast, high resistivity values correspond to the presence of fresh water. Significant areas with higher resistivity, mainly consisting of gravelly sand with potential. Fresh water identified at sites GG-01, GG-02, GG-03, GG-04, GG-05, GG-06, GG-07, GG-08, KA-01, KA-02, KA-03, KA-04, KA-05, KA-08, and KA-10 etc. These sites are favorable for freshwater exploration and are therefore recommended for test drilling.

Recommendations:

Following the successful analysis of the study area, several recommendations are proposed: Correlate data of this survey with borehole data for its validation. Allocate a groundwater budget specifically for water management in underdeveloped areas. Conduct a groundwater quality survey every five years under the supervision of the Ministry of Water and Power. Utilize vertical electrical sounding, electrical resistivity tomography, and seismic refraction techniques to increase confidence in the results. Ensure borehole data is publicly accessible for all underdeveloped areas. Launch a government awareness campaign to educate local communities about the importance of good quality water as soon as possible. Require government approval before installing new water tube wells in the area.

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