International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 12 Issue 9 ǁ September 2024 ǁ PP. 178-186

Granular Zone Delineation Using 2D Electrical Resistivity Tomography and Well Logging Techniques for Enhanced Groundwater Exploration

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Abstract
Electrical resistivity tomography (ERT) is a non-invasive geophysical method widely used for groundwater delineation in alluvium and hard rock formations. In addition, integration of the ERT with the geophysical well-logging technique helps to find and validate the obtained results. This study aims to find the aquifer using the geophysical 2D resistivity and well-logging methods. Two ERT survey lines were performed in Sikendarpur and Domodarpur, Ghazipur District, Uttar Pradesh, which had a length of 400m and an electrode spacing of 5m. Additionally, after the recommendation of the geophysical survey results, two boreholes were drilled at these locations. The two geophysical well-logging tools used in measuring in one run, are a natural gamma ray log, spontaneous potential log, and normal resistivity log (N64''). Only one borehole was executed at each location near the 2D resistivity lines. The saturated granular zones (51-100 Ωm) found from the 2D resistivity results were expected to be an aquifer, and the borehole records validated the zones.
Moreover, the porosity was calculated for all 2D resistivity lines, and imaging was created for each. Notably, the saturated zone in the study areas has a porosity more significant than 20%, suggesting the presence of a potential aquifer zone. The geophysical survey results were correlated with borehole records and are in good correlation. The study may be helpful in socially beneficial practices that can be utilized by non-profit organizations, scientists, and government agencies.
Keywords: *Well logging, ERT Electric Resistivity Tomography, Aquifer, groundwater.*

Date of Submission: 18-09-2024 Date of acceptance: 02-10-2024

I. Introduction

Water is a vital resource that contributes to the production of agricultural output, environmental health, and economic stability. Due to the significant decline in water resources in various parts of the world, regional water availability may become limited. In urban and rural areas, particularly in developing nations such as India, groundwater is a vital source of both irrigation and drinking water. India can meet its diverse water needs with a vast network of water bodies such as reservoirs, rivers, canals, ponds, and lakes (*Arora et al., 2023*). Unfortunately, its groundwater resources face significant challenges due to mismanagement, over-exploitation, and pollution (*Dixit et al., 2024*).

Groundwater undoubtedly provides a reliable, clean, and sustainable water resource. The increased water demand and groundwater interest in the last decade forced researchers to explore underground water regimes. Thus, the delineation of aquifer geometry and aquifer properties through geophysical techniques finds great expression in exploration. In the last three decades, major developments in geophysical resistivity methods have included providing realistic subsurface images in complex geological areas and alluvium formations. The development in the multielectrode resistivity meter equipment (*Griffiths et al., 1990; Dahlin, 1996*) and rapid inversion software (*Loke and Barker, 1996a, b*) bring out the widespread use of two-dimensional (2D) and even three-dimensional (3D) resistivity surveys.

Resistivity imaging is one of the prominent geophysical techniques used to map and delineate groundwater zones and their contamination, and it is also extensively used in environmental surveys (*Griffiths & Barker, 1993; Hamzah et al., 2006; Samsudin et al., 2000, 2001*). The 2D electrical resistivity survey is a widely recommended tool for finding lithological extent profiles. This survey employs multielectrode channels to generate a multidimensional map of the subsurface profile in an area. The prime use of this survey is to discover the subsurface profile, where the true subsurface resistivity can be determined by measuring the ground surface (*Loke, 1999*).

Resistivity methods are widely used in finding layer parameters in terms of layer thickness and corresponding layer resistivity. So, a resistivity survey can effectively determine the drilling site location (1D & 2 D). Among various rock geophysical properties, electrical resistivity is the most variable. Many geological parameters and factors contribute to such high subsurface resistivity variations. The type of formation, mineral content, fluid content, type of fluid, percentage of fracture filled with fluid, degree of fracturing, porosity and formation saturation, etc.

Generally, the conventional technique used in groundwater exploration is deep resistivity sounding (*Bhattacharya and Patra 1968; Zohdy et al. 1974; Telford et al. 1976; Parasnis 1986; Karous and Mares 1988; Giao et al. 2003; Kumar et al. 2007; Bhattacharya and Shalivahan 2016*) This technique yields and portrays subsurface information in terms of layers having various resistivities. With the improvement and advancement in technology, the electrical resistivity tomography (ERT) method has been successfully and frequently used for 2D subsurface imaging. This multielectrode channel technique displays a subsurface 2D slice in terms of resistivity distribution. In the past, the electrical resistivity tomography (ERT) method, a well-established resistivity imaging tool, has been widely employed for groundwater exploration (*Krishnamurthy et al. 2003; Kumar et al. 2014, 2016*) and environmental (*Singh et al. 2004; Leucci 2006; Cardarelli et al. 2010; Banerjee et al. 2011; Mondal et al. 2013; Singh 2013b; Sarma 2014; Bharti et al. 2015, 2016a, b, c*) study over different complex geological environments.

This study aimed to investigate and delineate the potential groundwater zones in the Damodarpur and Sikenderpur sites of the Ghazipur District of Uttar Pradesh. The study used 2D Resistivity imaging. This study employs the 2D resistivity method for locating the aquifer and the well-logging technique to cross-correlate the results.

II. Study Area

The study area lies on the bank of the river Ganges in Karanda Block of Ghazipur district of Uttar Pradesh. The area is part of the Central Ganga Plains. It can be described as a flat country with sloping slopes toward the NW-SE and drainage lines running along the route. The area slopes toward the Ganga River. The younger alluvial plain is located near the Ganga River. Numerous alluvium deposits characterize it, usually situated adjacent to flood plains. This region is mainly composed of younger unconsolidated materials. The groundwater table in this area is very shallow, and the groundwater yield prospect is excellent.

Various types of alluvium deposits, such as sand, clay, silt, and kankar, characterize this region's soil. The coarsest sediment is usually encountered in areas where streams have changed their course. Finer alluvium is also observed in older deposits. The presence of clay and loam characterizes uplands. The climate of the study area is characterized by a sub-tropical humid zone with hot and dry summers, a humid monsoon season, and dry winters. According to the Kppen–Geiger climate classification, this region is considered to be a Cwa (*Monsoon-influenced humid subtropical climate*). The temperature during winter ranges from 5 to 17˚ Celsius, while during the summer season, it can reach 42˚ degrees Celsius. The crops of the area are going through various activities throughout the year. The season for crops starts in July and ends in October. They are known as Kharif, while Rabi and the more common Jayad are usually established in March to June. Rice and wheat are the dominant crops, mainly irrigated by shallow tube wells and canals.

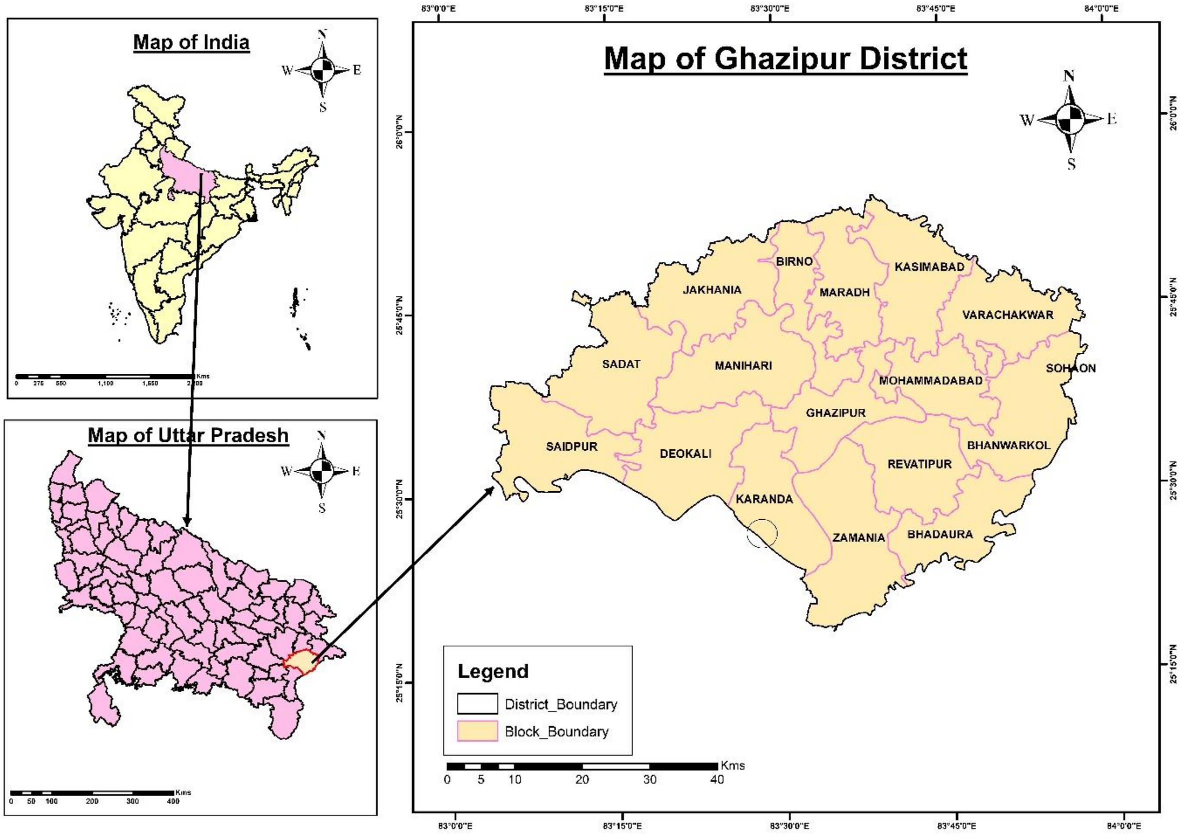

Fig.1 Location map of the study area.

Unconsolidated alluvial materials that have been exposed to saturation are the main sources of groundwater in the area. The water coming from these areas can be found in open wells that are supported by sand beds and clay kankar. Kankar, which occurs at shallow depths, can also yield water. Most of the shallow tubewells in the area rely on sandy horizons and kankar for their water supply. Groundwater extraction is observed in the study area is 32.94% and categorized as 'Safe'.

Fig.2 Google map location along the meandering river Ganges.

The Two ERT survey lines (Figure) were conducted on the right levees of the river perpendicular to the river flow at both sites Sikendarpur and Domodarpur. The total length of both lines (AA', and CC') is 400 m with 5 m electrode spacing. Near these sites, two boreholes have been drilled in villages Sikendarpur and Domodarpur at marked locations in the figure.

III. Materials and Methods

Electrical Resistivity Tomography (ERT) is a geophysical imaging technique that is used to generate 2D and 3D models, or subsurface resistivity images delineating resistivity distribution with depth. It is an advanced geophysics method used to determine the sub-surface's resistivity distribution by measuring the ground surface. Data collection is fast with an automated multielectrode resistivity meter. ERT profiles consist of a modelled cross-sectional (2-D) plot of resistivity (Ω·m) versus depth.

ERT surveys involve making a large number of four-point direct current (DC) electrical measurements (consisting of pairs of current and potential electrodes) using computer-controlled automated measurement systems and multielectrode arrays. These data are inverted to produce images of the subsurface; this is typically achieved by regularizing them. Nonlinear least-squares algorithms (e.g. *Loke and Barker, 1996*) in which the forward problem is solved using either finite element or finite difference methods.

The degree of fracturing, porosity, tortuosity, mineralogy, saturation, temperature, and groundwater resistivity affect subsurface materials' resistivity, thereby providing the basis for using ERT for geological and hydrogeological investigations. The use of ERT for characterizing subsurface geology is well documented, with many examples of investigating unconsolidated saturated sediments (e.g. Kilner et al., 2005; Froese et al., 2005).

Generally, the major litho-logical effect on resistivity in these types of sediments is the proportion and type of clay minerals (*Shevnin et al., 2007*), with increasing clay content causing a decrease in resistivity. The close link between resistivity and many important hydrogeological parameters and properties has led to the increased use of ERT for hydrogeophysical investigations, where it has been used to study groundwater quality (*Ogilvy et al., 2009*), moisture content (*Zhou et al., 2001*), and in-situ remediation (*Daily and Ramirez, 1995*).

The 2D electrical resistivity tomography technique maps the vertical and lateral variations in lithofacies.In the electrical resistivity tomography technique, a precise subsurface two-dimensional (2D) model is obtained where the resistivity changes in vertical and horizontal directions along the survey line. The 2D resistivity imaging survey is a practical and economic compromise for obtaining precise results while decreasing survey costs. 2D imaging survey techniques with higher data density (100 to 500) measurements within a 400 m stretch are obtained, with an electrode separation of 5m.

IV. Results and Discussion

4.1 ERT Survey

This research performed an Electrical Resistivity Tomography (ERT) survey along a 400-meter profile, employing two electrode configurations: Gradient and Wenner. The main objective was to locate medium to high resistivity areas likely linked to groundwater zones inside alluvial deposits. The survey line, P1-P2, was deliberately oriented in a north-south orientation to enhance data clarity and proximity to the Ganga River flood zones.

The results from both configurations were consistent, indicating two high-resistivity zones with values between approximately 50 and 200 Ohm.m, which suggest the existence of underground groundwater aquifers. The low resistive areas signify clay deposition varying from around 12 to 28 ohm.m. Figures 3 and 4 illustrate the 2D resistivity sections for the Gradient and Wenner configurations at the Damodarpur site, and just the gradient profile for the Sikanderpur site, respectively. Both profiles illustrate a distinct subsurface resistivity distribution, effectively pinpointing regions of prospective aquifers or hydro-geological significance.

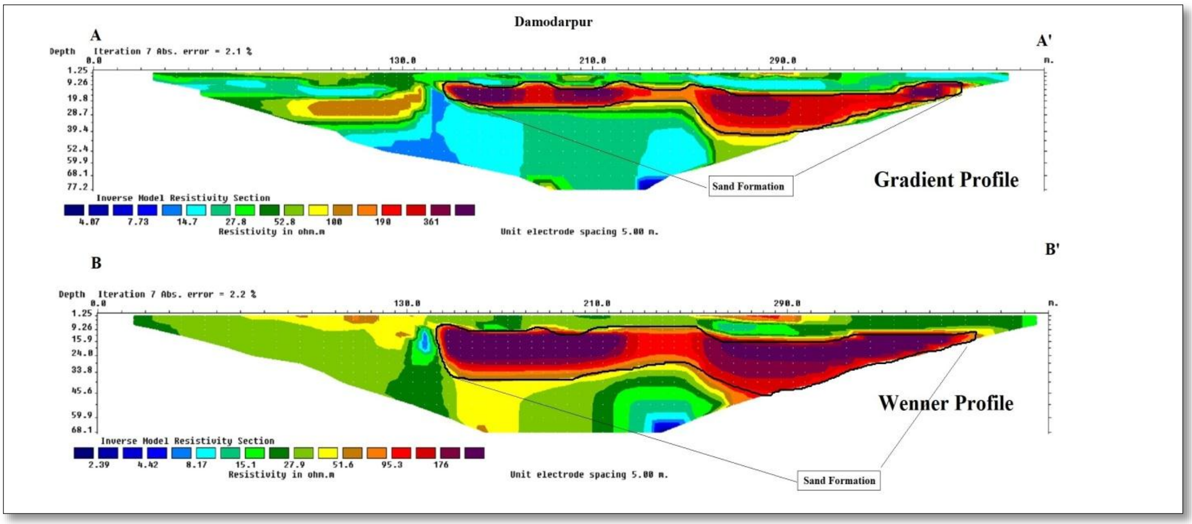

Fig.3 2D-Resistivity section of the Gradient and Wenner profile at the Damodarpur site.

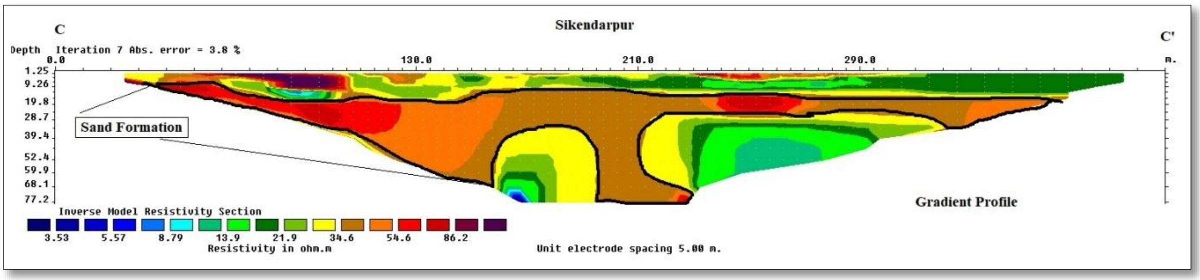

Fig.4 2D-Resistivity section of the Gradient and Wenner profile at the Sikenderpur site.

4.1.1 Resistivity and Depth Analysis

The resistivity data were further analysed to interpret subsurface geological structures concerning depth:

Damodarpur (Profile AA' and BB')

High Resistivity Zones: Areas exhibiting resistivity values approximately 50 to 200 Ohm.m were identified at depths ranging from approximately 9.20 to 45.50 meters below ground level. These granular zones correspond to a sand aquifer with an increased likelihood of groundwater availability. These strata are interposed between the upper and lower sandy clay, as illustrated in the Wenner profile BB' in Figure 3.

Low Resistivity Zones: Regions exhibiting resistivity below approximately 30 Ohm.m were identified at depths ranging from the surface to 9.20 mbgl and thereafter from 45.5 to 68.1 mbgl, as illustrated in profile BB' in figure 3. These zones may signify the existence of clay-rich soils and partially saturated formations.

Sikendarpur (Profile CC')

High Resistivity Zones: Areas exhibiting resistivity values about 34.6 to 80 Ohm.m were identified at depths ranging from approximately 9.26 to 72.2 meters below ground level. These granular zones correspond to a sand aquifer with an increased likelihood of groundwater availability. The layers are interposed between the upper and lower sandy clay, as illustrated in the Wenner profile BB' in Figure 4.

Low Resistivity Zones: Regions exhibiting resistivity below approximately 30 Ohm.m were identified at depths ranging from the surface to 9.20 mbgl and thereafter from 45.5 to 68.1 mbgl, as illustrated in profile BB' in figure 3. These zones may signify the existence of clay-dominant soils and partially saturated formations.

These interpretations indicate a layered geological formation, with potential aquifers situated between impermeable strata, rendering the site a viable option for groundwater extraction.

4.1.1 Conclusion

The ERT geophysical surveys at Damodarpur and Sikendarpur reveal that high resistivity zones (50-200 Ohm.m in Damodarpur and 34.6-80 Ohm.m in Sikendarpur) at depths ranging from 9 to 72 meters suggest sand aquifers with significant groundwater potential, making them ideal for drilling and water extraction. In contrast, low resistivity zones (<30 Ohm.m) found near the surface and at deeper levels indicate clay-rich formations or partially saturated layers, which have limited permeability and are less suitable for groundwater development. Therefore, drilling should focus on the identified high resistivity zones for optimal water yield.

The ERT survey has provided critical insights into the subsurface resistivity distribution, identifying zones with potential geological and hydrogeological significance. These findings are invaluable for groundwater exploration, environmental assessments, and engineering projects. However, additional geophysical surveys like well logging may be required to further substantiate these interpretations.

4.2 *Well-Logging Survey*

The key parameters measured in geophysical well-logging include spontaneous potential (SP), natural gamma-ray (NGR), and resistivity logs. These tools offer a more detailed understanding of subsurface conditions, which can be used to delineate the boundary between freshwater and saltwater, identify karst zones, and assess the hydraulic properties of aquifers.

4.2.1 Gamma Ray Logging

Gamma-ray logs measure the natural radioactivity in formations, providing an estimate of shale content and helping to differentiate between water-bearing and non-water-bearing layers. These measurements are crucial for hydrogeological exploration as they help identify zones with varying levels of permeability.

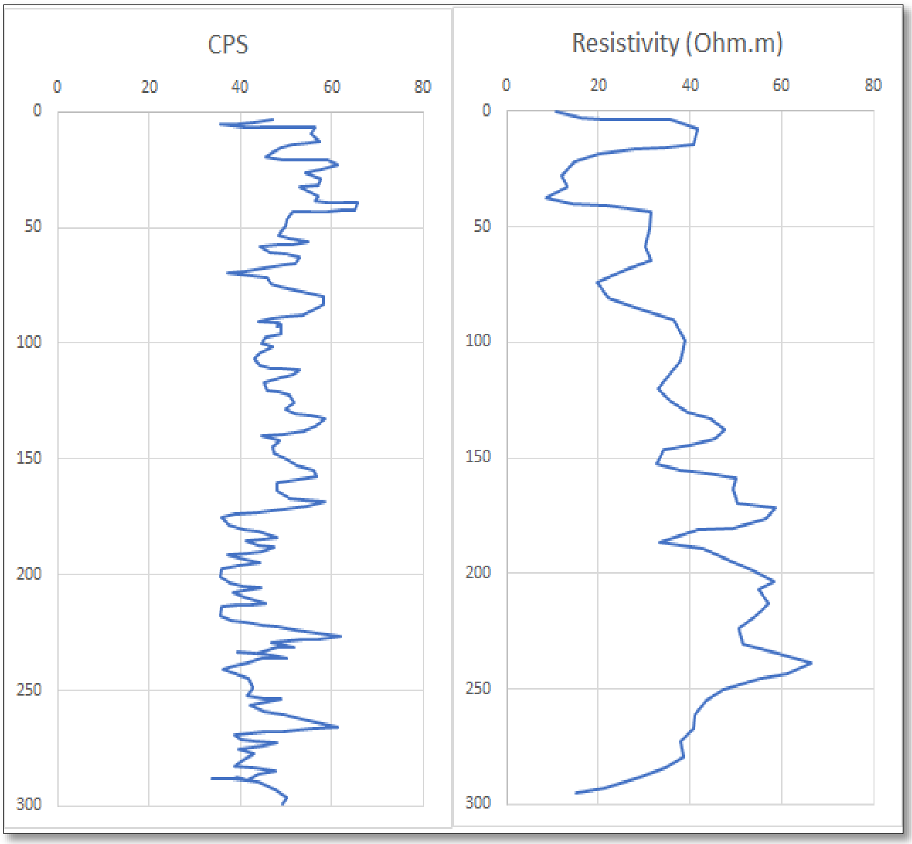

Fig.5 Well log chart of Damodarpur site.

4.2.2 Spontaneous Potential (SP) Logs

SP logs capture natural voltages generated by the interaction between formation water and drilling fluids. These logs provide valuable insights into the salinity of formation waters and the lithological properties of the formation.

4.2.3 Normal Resistivity Logging

Using a four-electrode system, normal resistivity logs measure the apparent resistivity of geological formations. The 16-inch and 64-inch normal resistivity measurements help partition different lithological units, distinguishing between more resistive and conductive layers, vital for groundwater exploration.

Implications of Well-Logging

The borehole drilled at Damodarpur, located near the ERT site, reached 300 meters below ground level (mbgl) compared to the reported drilled depth of 305 mbgl. Gamma logs and long normal (N64") resistivity measurements were recorded using a UPTRON logger. Based on the electrical log data, the following granular zones are recommended for well construction: Prominent granular zones: 9-25 mbgl, 47-70 mbgl, 75-145 mbgl, 155-178 mbgl, and 191-250 mbgl. Clay zones mixed with kankar and silt: 25-47 mbgl, 70-75 mbgl, 145-155 mbgl, and 178-191 mbgl.

At Sikendarpur, also near the ERT site, the borehole was logged to 300 mbgl with the drilled depth of 305 mbgl. Self-potential (SP) and long normal (N64") resistivity measurements were obtained using the UPTRON logger. Based on these logs, the following granular zones are recommended for well construction: Prominent granular zones: 11-19 mbgl, 55-135 mbgl, 138-167 mbgl, and 207-270 mbgl. Clay zones mixed with kankar and silt: 19-55 mbgl and 167-207 mbgl.

The SP profile indicates moderate development and resistivity values range from moderate to high, suggesting a compact and potentially permeable formation, although partial permeability cannot be excluded.

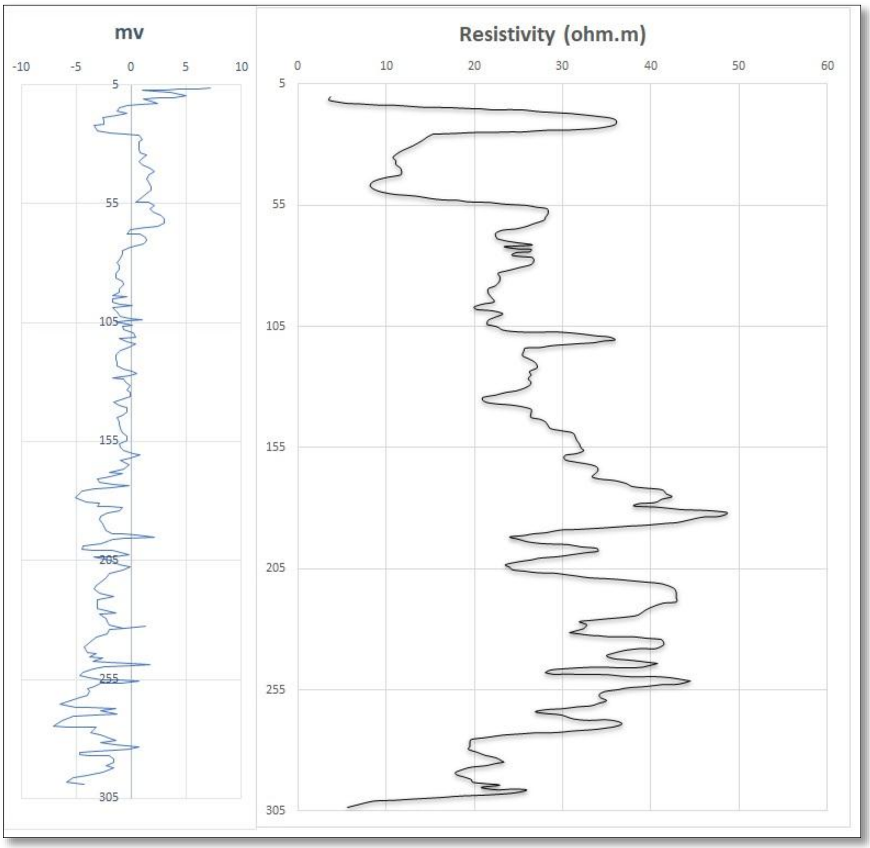

Fig.6 Well log chart of Sikanderpur Site.

The integration of Electrical Resistivity Tomography (ERT) and well-logging techniques provides a comprehensive understanding of the subsurface hydrogeology, the assembly for groundwater abstraction has been given for both deep exploratory well that is ~270m and shallow observation well for ~80m. ERT offers a broad perspective on resistivity variations, while well-logging provides detailed, fine-scale measurements, enhancing the accuracy of hydrogeological assessments. This combined approach significantly improves the identification of groundwater-bearing formations, especially in rural areas with limited water supply.

V. Conclusion

In conclusion, the results from the ERT and well-logging studies underscore the potential for further groundwater exploration in the region. These findings will guide future drilling plans and inform aquifer management strategies to optimize groundwater resources and ensure sustainable water supply. The integration of Electrical Resistivity Tomography (ERT) and well-logging techniques has detailed characterization of the subsurface geology in Damodarpur and Sikendarpur, revealing valuable insights into potential groundwater resources.

Overall, the combined use of ERT and well-logging has proven effective in delineating groundwater-bearing formations and understanding subsurface geology. This integrated approach provides a comprehensive view of resistivity variations and fine-scale measurements, significantly enhancing hydrogeological assessments. The findings indicate that both Damodarpur and Sikendarpur are promising sites for groundwater extraction, with stratified aquifer systems that could be effectively tapped for sustainable water supply. Future groundwater exploration and management efforts should consider these detailed insights to optimize resource utilization and address water supply challenges in the region.

Acknowledgments
The authors are grateful to the Chairman, CGWB, and the Regional Director, NR, CGWB for his invaluable support and permission to research and publish the work.

Statements and Declaration
Funding: The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.
Competing Interests: The authors have no relevant financial or non-financial interests to disclose.
Author Contributions:
Anirudh Singh and Rajesh Babu: Fieldwork Conceptualization, Methodology, Technical Investigation, Software, Figures, Original draft preparation; **Shashi Kant Singh: and Mayank Dixit** Conceptualization, Methodology, Original draft preparation.

Ethical Approval: This is not applicable because this article contains no studies on human or animal subjects.
Consent to Participate: The research data were not prepared through a questionnaire.
Consent to Publish: The paper's author has no conflict of interest and no conflict in submitting the final version.
Availability of data and materials: Data can be obtained at the request of the Regional Director, NR, and CGWB.

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