Journal of Nepal Hydrogeological Association (JNHA), Vol (2), 127-143 (2025)
ISSN: 3059-9725 (Online)
https://doi.org/10.3126/jnha.v2i1.85392
RESEARCH ARTICLE

Mapping aquifer zones in the Terai region of Nepal using the natural electromagnetic field technique: A case study from Rajbiraj Municipality, Saptari

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***(Submission Date**: 20 July , 2025; **Accepted Date:** 25 August, 2025)*

ABSTRACT

This research paper demonstrates the application of the Natural Electromagnetic Field Frequency Selection System (specifically the PQWT-TC150 instrument) for mapping aquifer units in the Terai region of Nepal. The electromagnetic method, utilizing very low frequency (VLF) signals (0–30 kHz), was employed to delineate groundwater-bearing zones through resistivity contrasts in Quaternary alluvial sediments of Rajbiraj Municipality, Saptari District. Three survey profiles identified low-resistivity anomalies indicative of productive saturated formations below 15 m depth. This aquifer depth can be correlated with the nearby borehole and results from the existing literatures. Based on the lithological composition and hydrogeological characteristics, the present study area lies in the transition zone between the Bhabar Zone and Middle Terai. The Bhabar Zone characterized by coarse, permeable sediments has low (seasonal) drainage density, as it facilitates rapid groundwater recharge, whereas the Middle Terai has dense drainage network as the river gains water in this region, due to presence of fine-grained sediments, promoting higher storage capacity but slow flow rates. This quick non-invasive technique offers significant socio-economic benefits as it reduces costs and risks associated with drilling. It aids to prevent financial losses caused by unsuccessful drilling. This saves time and resources.

Keywords: ***Aquifer mapping, Groundwater exploration, Natural electromagnetic field, Terai region, Bhabar zone, Middle Terai zone, Aquifer mapping***

INTRODUCTION

The Terai region of Nepal, a northern extension of the Indo-Gangetic Plain, hosts vital aquifer systems that sustain agriculture, industry, and >50% of Nepal's population. In Nepal, like many developing countries, agriculture remains the backbone of the economy. Nearly 60% of the working population depends on farming for their livelihood, and the agriculture sector contributes 23.92% of the nation's Gross Domestic Product (GDP) (Yogi et al., 2025).

Among the arable land with irrigation facilities, 65.7 percent have surface irrigation infrastructures, while 34. 1 percent have groundwater irrigation infrastructures (Economic Survey 2023/24). For industrial, drinking, and agricultural uses, groundwater is the primary supply of water (Shrestha et al., 2018). But as extraction rates have increased, water tables have dropped and water quality has deteriorated due to contamination from industrial discharge and agricultural runoff.

A geological structure is considered permeable when there are interconnected empty spaces in the ground. More groundwater is stored and produced by an aquifer with higher porosity and permeability (Wright, 1992). In natural condition, gravity pulls groundwater downhill. However, the groundwater can flow from low elevation to higher elevation under artesian condition (Alley et al., 2002; Guru et al., 2017).

The present study area located in Rajbiraj Municipality, 09 lies on quaternary alluvial deposit. These Quaternary alluvial aquifers exhibit high heterogeneity, with productivity varying across the Bhabar, Marshy, and Southern Terai subzones (Pathak, 2016). There have been a few studies that look into how groundwater is being explored and used in such region. Traditional drilling methods for aquifer characterization are costly and spatially limited. Geophysical techniques like the Electromagnetic Field method offer rapid, non-invasive alternatives by measuring resistivity contrasts between saturated and unsaturated sediments (Reynolds, 2011).

This paper evaluates the Near Electromagnetic Fied technique using the PQWT-TC150 instrument to map aquifer units in Rajbiraj Municipality (Saptari District) in delineating aquifer depth, and lithological constraints. Geoelectric parameters (thicknesses and resistivities) of subsurface layers and aquifer zones were ascertained by conducting a thorough electromagnetic survey. The results thus obtained aids in identifying precise drilling location for the drilling companies by knowing the thickness and position of the aquifers. Using the PQWT-TC150 groundwater detector equipment and the Magnetotelluric method of passive electromagnetic techniques, which image the subsurface condition up to 300 m, the goal of this paper is to determine the aquifer zone for groundwater resources management in Rajbiraj Municipality by correlating with existing borehole logs.

Study Area

The study area is located near the Rajbiraj Industrial Area, Rajbiraj Municipality-09, Saptari District of Madhesh Province (Fig. 1). The geographical location of the study area is 26°34'24.78"N, 86°44'8.60"E.

Geologically, the study area is located within the Quaternary alluvial river deposits of Nepal’s Terai region, which forms part of the Ganga foreland basin. Composed of Pleistocene to Holocene sediments, the Terai Plain extends south of the Siwalik Hills. The region's elevation gradually decreases from 100–200 m (east to west), with a general southward slope.

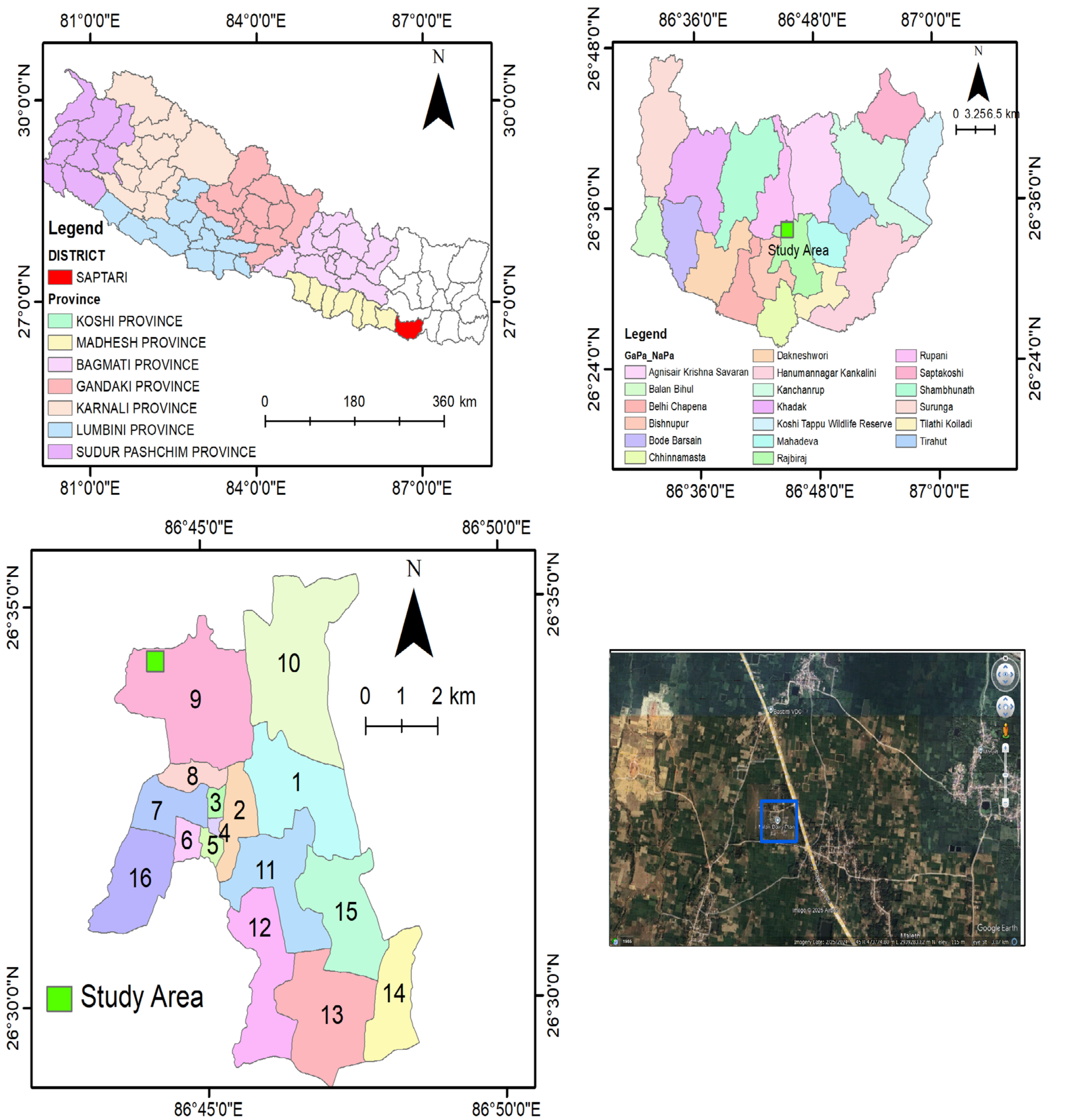

Fig. 1: Map of Nepal showing Saptari District (Study area)

Based on depositional characteristics, the Terai can be divided into three distinct zones (Fig. 2), from south to north as,

i. Bhabhar Zone – Proximal to the Siwaliks, characterized by coarse, permeable sediments (boulders, cobbles and pebbles).

ii. Middle Terai – Intermediate area with mixed sedimentology.

iii. Southern Terai – Distal fine-grained deposits (sand, silts and clay), representing typical Gangetic plain.

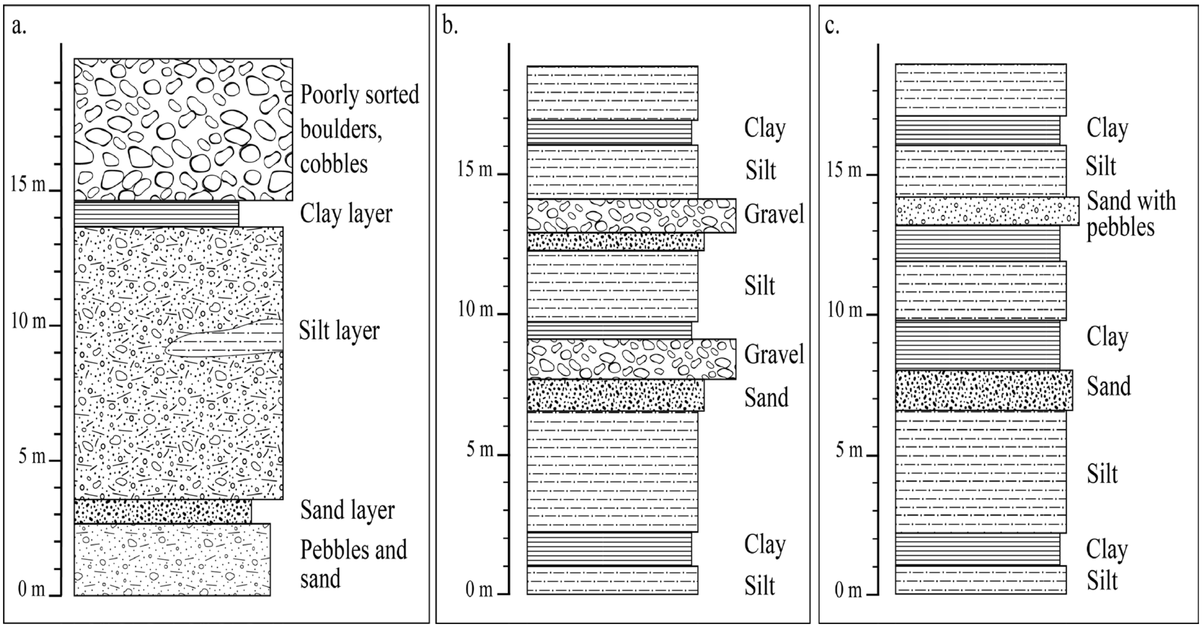

Fig. 2: Generalized lithologs of (a) Bhabar Zone, (b) Middle Terai, and (c) Southern Terai of Nepal (modified after Pathak, 2016)

Specifically, the study area lies on the boundary between the Bhabar Zone and the Middle Terai, comprising of Pleistocene–Holocene boulders, pebbles, cobbles, sand, silt and clay derived from the Siwalik Hills. The Bhabar zone acts as a primary recharge area for Terai aquifers but exhibits seasonal water table fluctuations (Upadhyay and Sah, 2012). The Middle Terai represented by the presence of gravels and sand, alternating with red, black and yellow clays is a marshy land where artesian condition prevails (Sah, 2015). Unconsolidated loose sediments of Terai and inner Terai, karstified and fractured carbonate rocks of midland and Tethys group has developed good potential source for groundwater. The Siwaliks and non-karstic but fractured carbonate rocks in Lesser Himalaya and Tethys Group acts as moderately productive aquifers. Unfractured high-grade rocks of Midland Group and crystalline rocks of higher Himalaya are considered to constitute poor aquifer quality formations (Shrestha et al., 2018).

The study area exhibits dense network of seasonal streams (hydrologically active during the monsoon period) with the Koshi river and Khado Khola being the perennial (Fig. 3). The drainage pattern initially follows a north-south direction before shifting to west-east, as seen in major rivers like the Koshi. Additionally, the study area features numerous lentic water bodies (ponds), likely formed by depression filling, and groundwater seepage.

Objectives

The main purpose of this study is to identify subsurface geological features associated with water-bearing zones (aquifers) to facilitate the extraction of a sufficient volume of water, as well as to determine suitable drilling locations and depths for effective groundwater resource exploitation

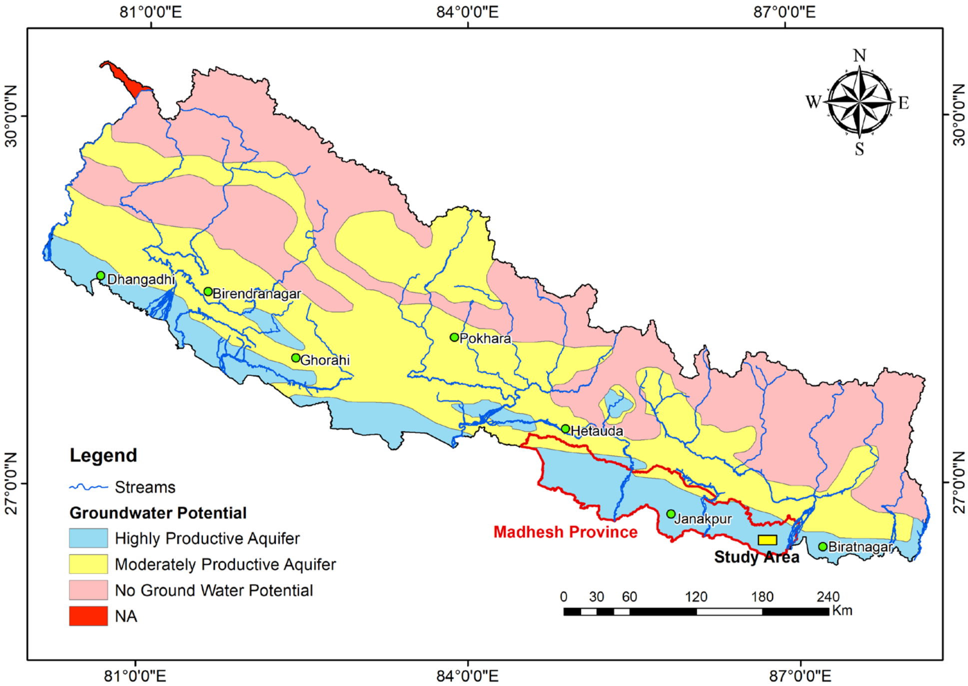

Fig. 3: Groundwater potential map of Nepal (modified after Shrestha et al., 2018)

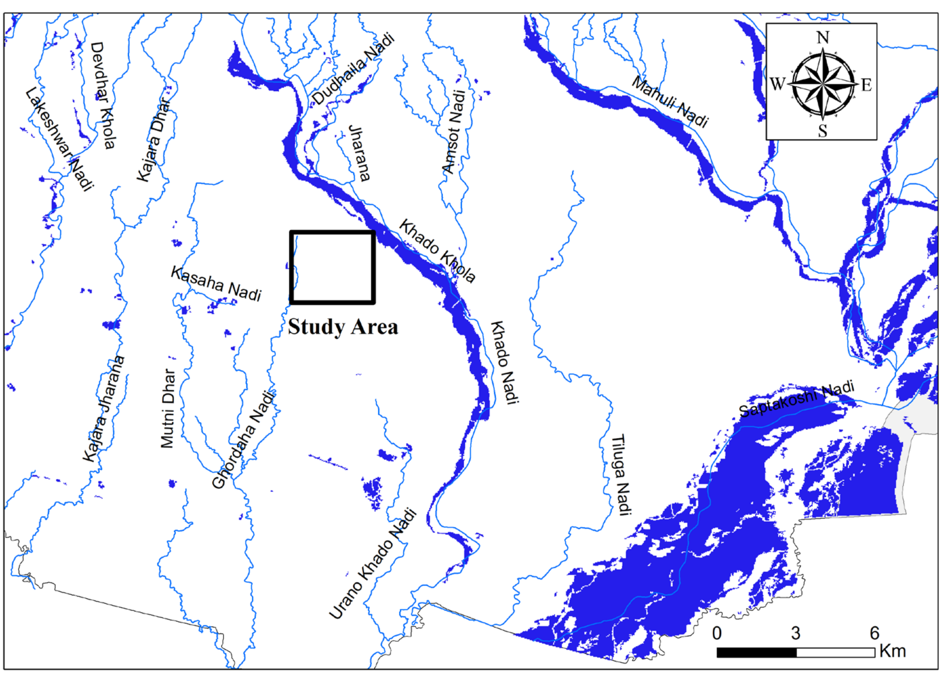

Fig. 4: Drainage map of the study area and adjacent regions

Material and Methods

Natural Electromagnetic Field Technique

The PQWT-TC150, a novel geophysical exploration instrument (Fig. 5), was used to assess the electromagnetic field in the study area. The instrument utilizes the theory of Electromagnetic Field (NEF) for geophysical exploration, primarily for detecting subsurface water resources. This method is based on the principle that variations in the Earth's natural electric and magnetic fields can reveal differences in the conductivity properties of underground geological structures.

The PQWT-TC150 uses the natural electromagnetic field variations (0–30 kHz) as its primary field source. This electric field is influenced by the Earth's steady magnetic field, which is primarily generated by the self-sustaining geodynamo action within the Earth's liquid outer core.

The PQWT technology integrates three key geophysical methods (Heilig et al., 2018):

1. **Nuclear Magnetic Resonance (NMR)**: This principle involves nuclei in a strong constant magnetic field being perturbed by a weak oscillating magnetic field. They then respond by producing an electromagnetic signal with a frequency characteristic of the magnetic field at the nucleus. The performance of NMR is dependent on the magnitude of the natural geomagnetic field, the electrical conductivity of rocks, and electromagnetic noise.

2. **Magnetotelluric (MT)**: This method measures the electrical differences of the natural Earth's magnetic field and their variations at different frequencies and depths. The PQWT-TC150 passively measures the electric (E) and magnetic (B) fields in an orthogonal direction at the ground surface using two non-polarizable potential electrodes. The geomagnetic field is considered a plane wave, perpendicular to the ground and distributed far from the source.

3. **Induced Polarization (IP)**: Induced polarization generally involves observing the voltage response in the ground after the cessation of an applied current, which can indicate the presence of certain minerals or fluid-filled pores.

Measurement and Interpretation

Data Acquisition: The precise location of each Electromagnetic survey profile station was determined and recorded using a Garmin 64 Global Positioning System (GPS) device. The core of the electromagnetic method employed is the measurement of the Earth's natural electric field. This technique, often referred to as the natural electric field method, involves selecting a specific frequency for measurement. The equipment, described as a "potential frequency of detecting instrument" or "natural selected frequency electric field instrument," is designed for geological exploration. A significant advantage of this instrument is its reliance on the Earth's natural electromagnetic field as a source, eliminating the need for an artificial power supply system. This design choice contributes to a simpler and lighter instrument, enhancing its portability and ease of use in the field. The PQWT-TC150 (Hunan Puqi Geologic Exploration Equipment Institute, China) measures the electric field component of thirty-six different frequencies in the geomagnetic field in millivolts (mV). This is achieved by placing two potential electrodes (N and M) 10 meters apart on the ground to take initial readings, and then moving them progressively along a traverse line (Fig. 6).

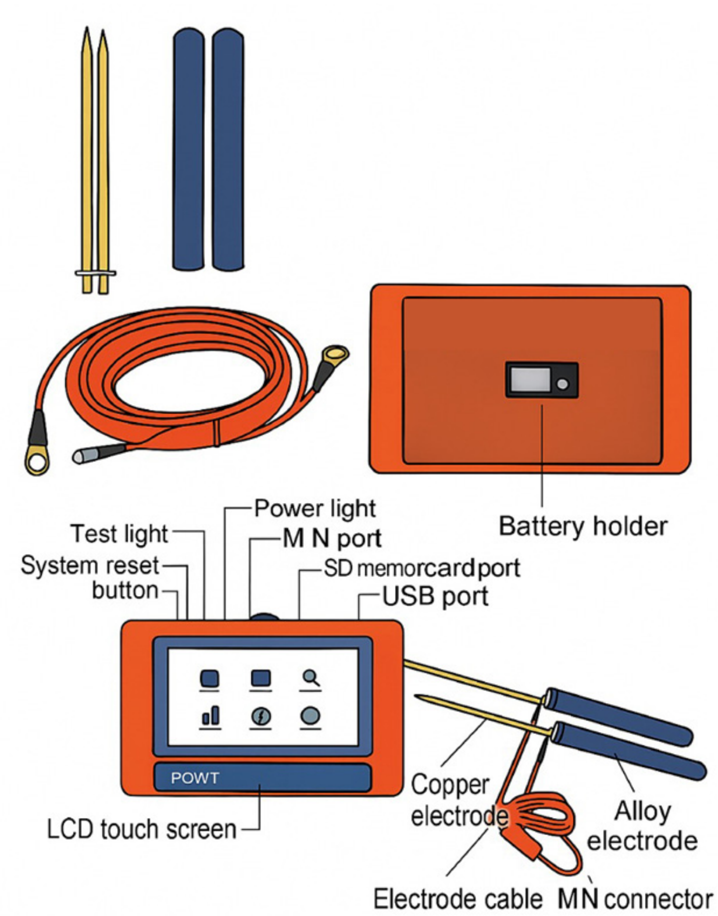

Fig. 5: Equipment (PQWT-TCP150) used for VLF survey

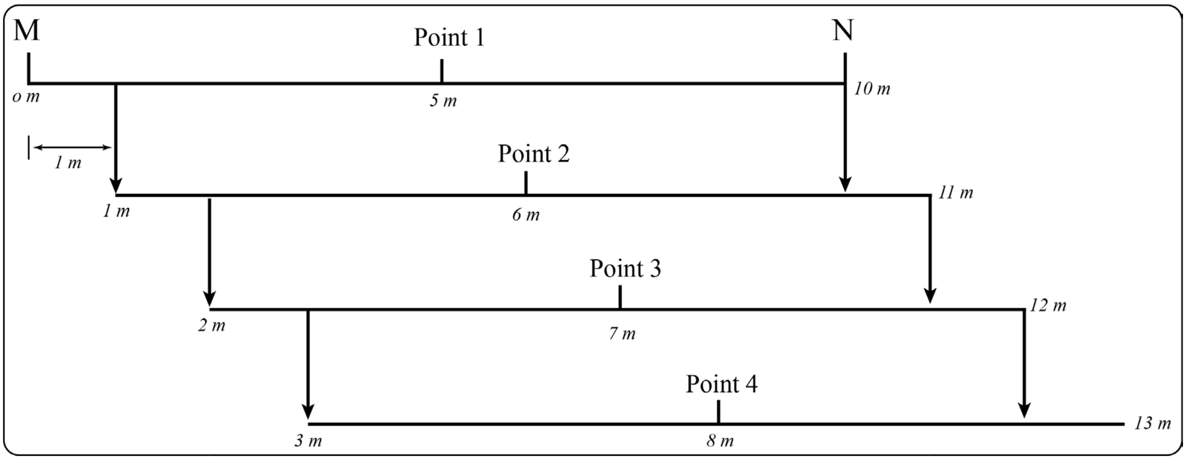

Fig. 6: Field setup and measurements

Resistivity Calculation: The instrument calculates the resistivity structure of the Earth based on the ratio of the horizontal electric field (Ex) and the magnitudes of the magnetic field (Hy). This relationship is derived from Cagniard's scalar resistivity formulae, given by (Cagniard, 1953; Waff, 2000):

$$r_m = \frac{1}{5f} * \left(\frac{E_x}{H_y}\right)^2$$

Where:

r_m is the resistivity of the medium under interaction,

f is the operating frequency, and

Ex and Hy are the electric and magnetic field components, respectively.

Depth of Penetration: The penetrating depth (d) of plane electromagnetic waves is directly proportional to the resistivity of the media at a constant frequency, as described by:

$$d = 503.3\sqrt{\frac{r_m}{f}}$$

Where:

d is the depth of penetration,

r_m is the resistivity of the medium,

f is the frequency,

This equation allows for a one-dimensional depth inversion, assuming a homogeneous, isotropic, and horizontally layered ground.

The study area displays inherent heterogeneity due to lateral and vertical variations in grain size of deposited alluvial sediments along with varying depositional patterns. Though, the equation provides a theoretical approximation, we acknowledge that anisotropy and heterogeneity exist in the study area.

Profile Mapping: The PQWT-TC150 generates a frequency curve and a profile map.

Frequency Curve: This plots the frequency responses of the Earth's electromagnetic field (in mV) against the lateral sampling distance. A straight line indicates a homogenous subsurface, while curvy or angular lines suggest variations in rock properties.

Profile Map: This pictorial interpretation uses a resistance bar (red at the top for highly resistive zones, transitioning to blue at the base for low resistive zones). Regions with concentrated blue color indicates high tendency for groundwater, while concentrated contour lines at the bottom layer suggest high resistive rock formation/coarse sediments.

Results

Three surveys were carried out in the study area. The cable layout alignment is shown in Fig. 7. The V-shape curve of the measured electromagnetic values (distance vs potential difference) for each profile were plotted with several color bands showing different frequency levels. The peak anomaly indicates the higher resistivity, presumed to be the geological structures of unsaturated features in the area. The sink V-shape curve indicate an anomaly with groundwater features, presenting low resistivity values pointing down. This sinking zone is termed the water bearing formation that will be viable for groundwater potential (Fig. 9, Fig. 12 and Fig. 15). The lithological description is based on field observation and nearby borehole logs (Fig. 8).

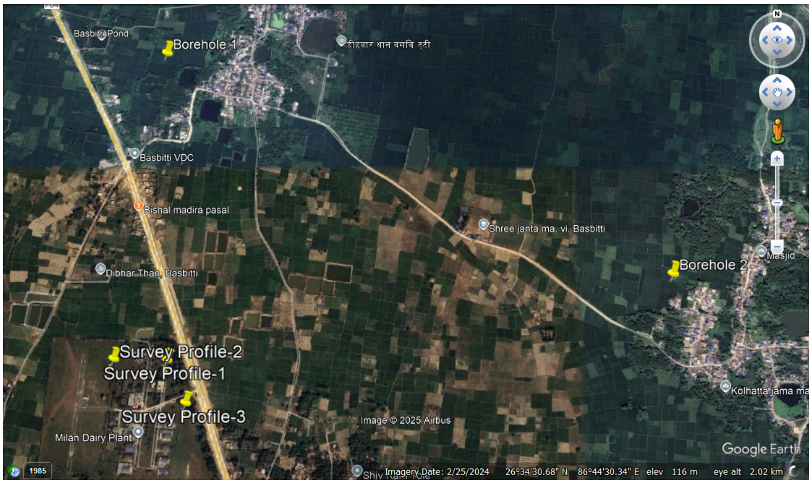

Fig. 7: Survey profiles on Google Earth Image along with nearby borehole locations

Survey Profile-1

The iso-resistivity profile map shows electric potential values (in millivolt) up to the depth of 150 m. Three subsurface layers can be delineated: saturated, partially saturated and unsaturated geological formations (Fig. 10 and Fig. 11). Clay/silty clay to dry sand and gravel is expected at the top layer. The second layer with low resistivity zone at 40-50 m depth indicates saturated sand with few gravels. The saturated layer is followed by mixture of gravel-sand-silt, sandy gravel and cobbles boulders up to 150 m depth.

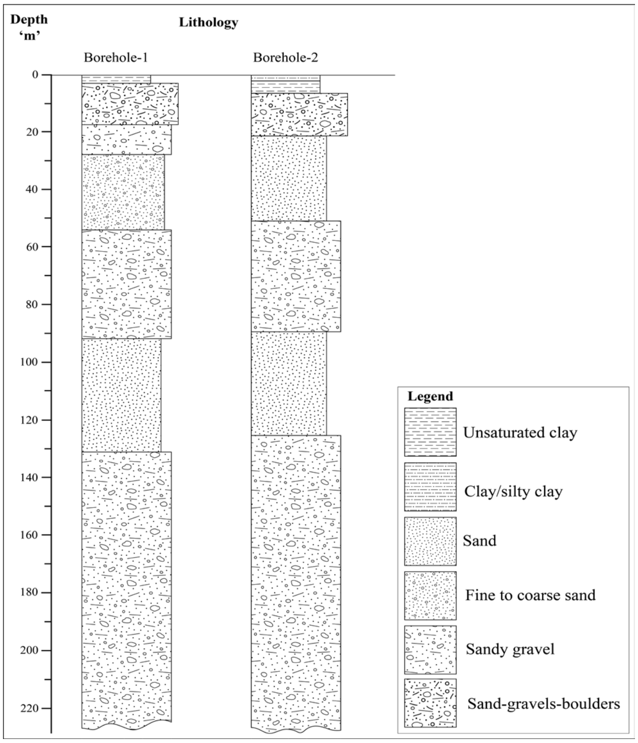

Fig. 8: Borehole logs around the study area

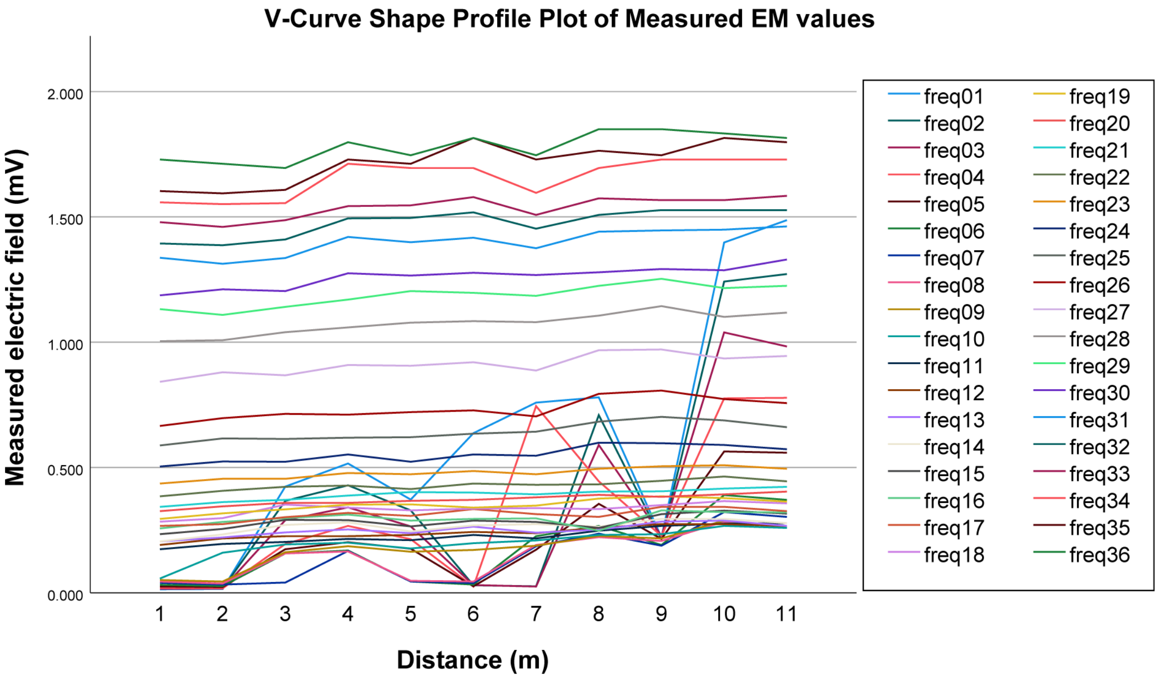

Fig. 9: Measured electric potential values with distance (Profile-1)

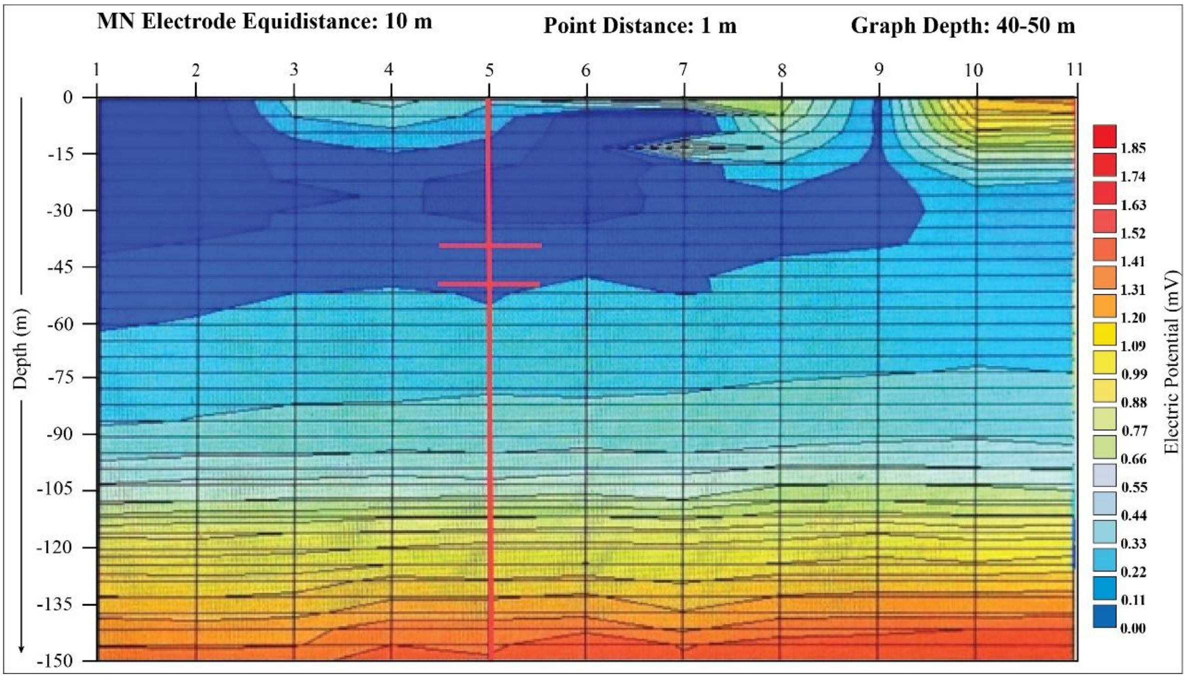

Fig. 10: Iso-Resistivity Profile Map (Profile-1)

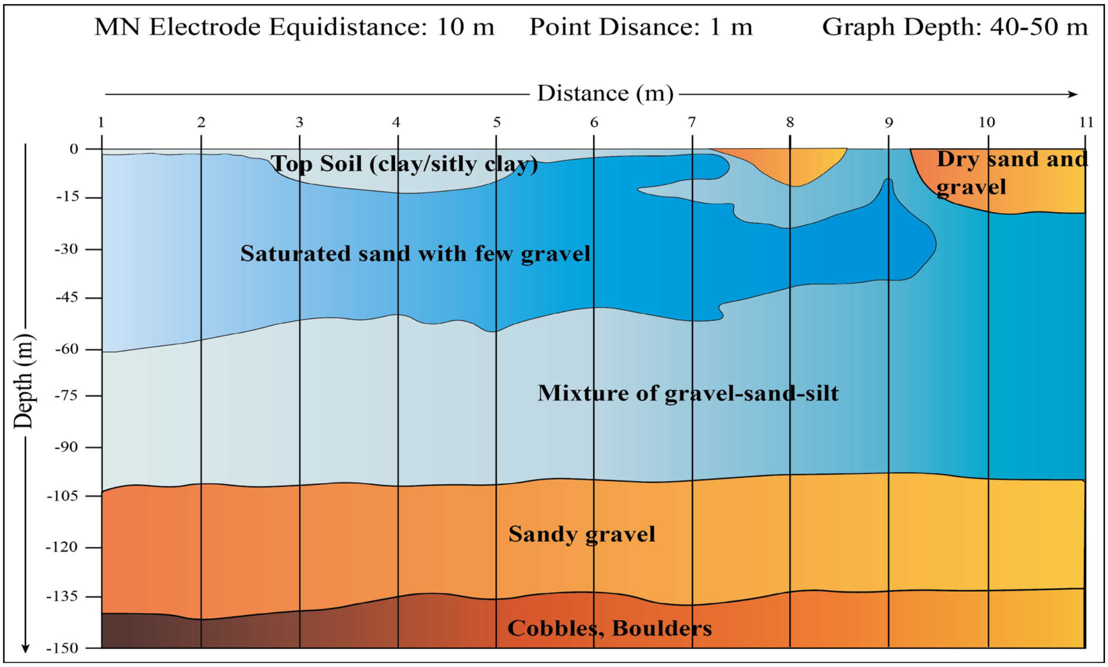

Fig. 11: Lithological Description (Profile-1)

Survey Profile-2

From iso-resistivity profile map, 3 subsurface layers can be delineated: saturated, partially saturated and unsaturated geological formations (Fig. 13 and Fig. 14). Clay/silty clay is present as the top layer up to about 15 m depth. At the second layer, mixture of gravel-sand-silt is expected. From 70 m to 100 m depth, saturated sand with few gravel is expected. From 100 m to about 135 m depth, saturated sandy gravel is expected. From 135 m to 150 m depth, cobbles and boulders are expected.

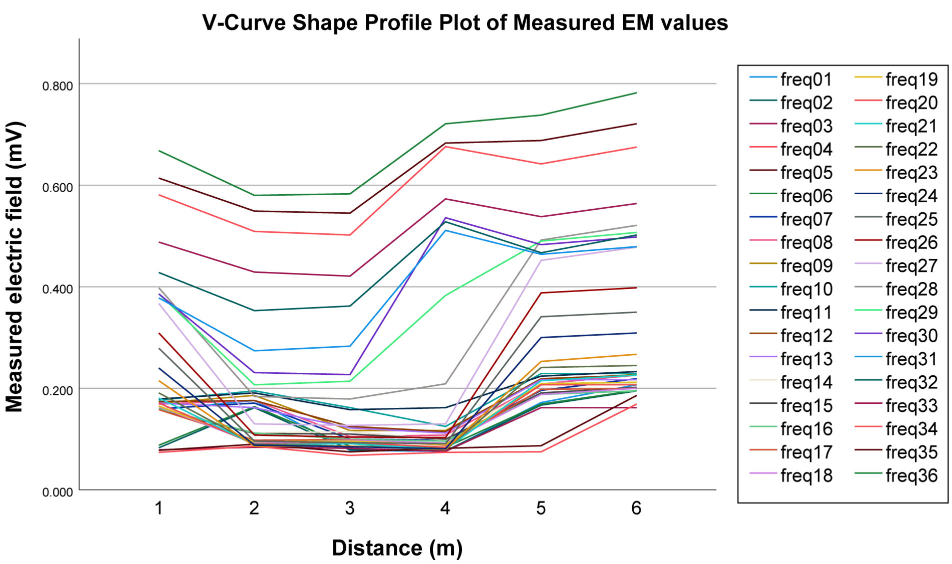

Fig. 12: Measured electric potential values with distance (Profile-2)

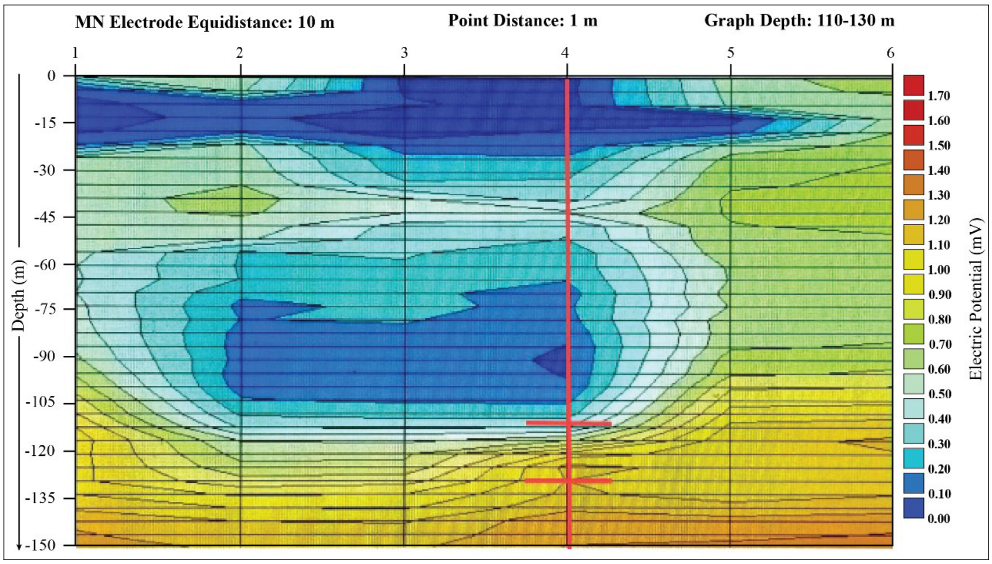

Fig. 13: Iso-Resistivity Profile Map (Profile-2)

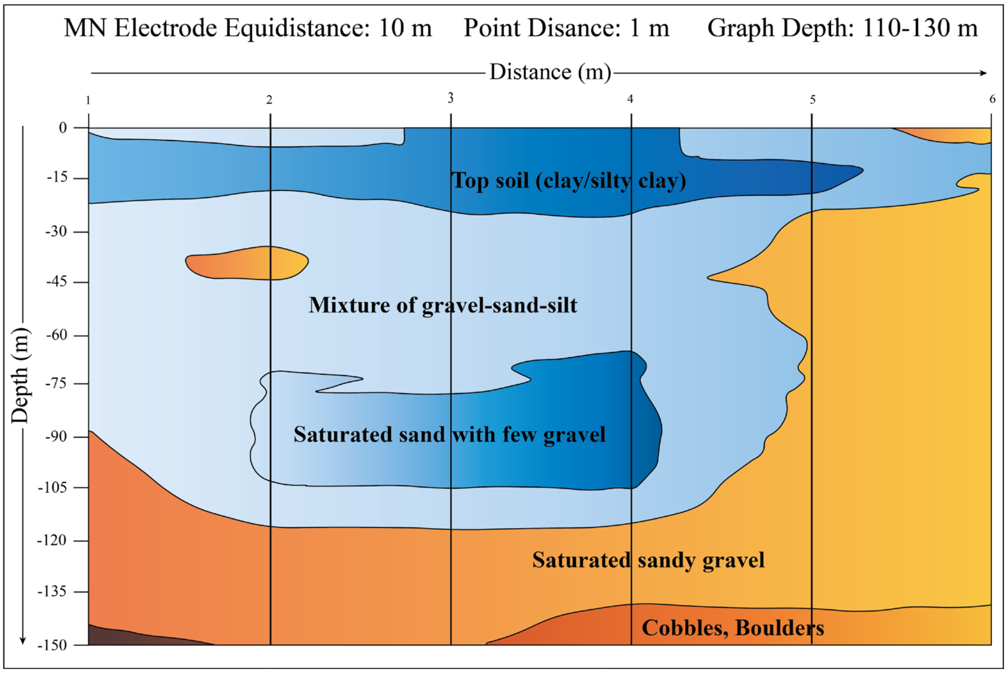

Fig. 14: Lithological Description (Profile-2)

Survey Profile-3

From iso-resistivity profile map, 2-3 subsurface layers can be delineated: saturated, partially saturated and unsaturated geological formations (Fig. 16 and Fig. 17). Clay/silty clay is expected at the top layer up to about 5 m depth. Saturated sand and gravel is expected as second layer up to about 270 m depth. From 270 m to 300 m depth, saturated silt-sand-gravel layer is expected.

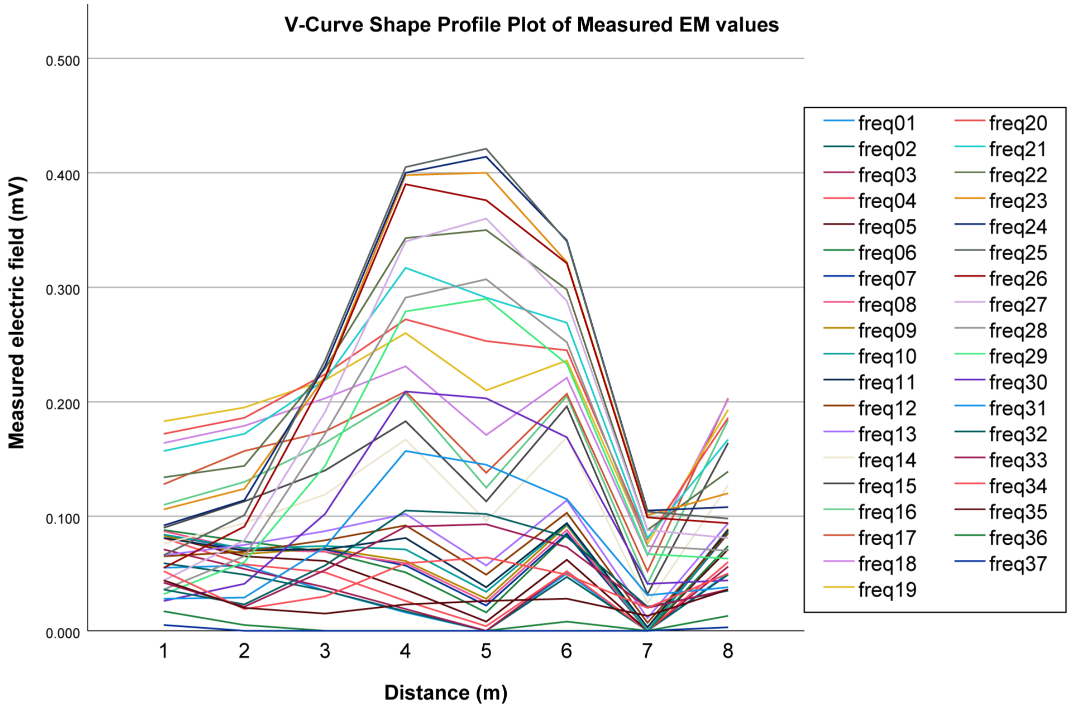

Fig. 15: Measured electric potential values with distance (Profile-3)

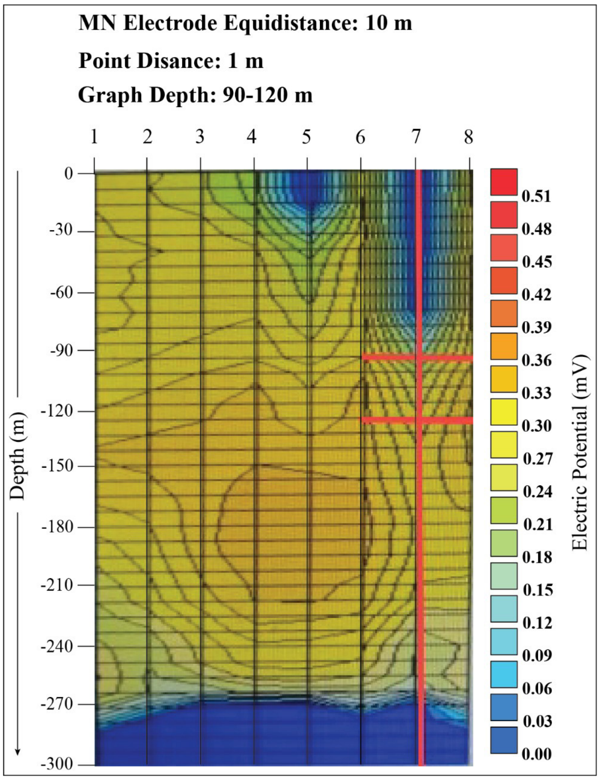

Fig. 16: Iso-Resistivity Profile Map (Profile-3)

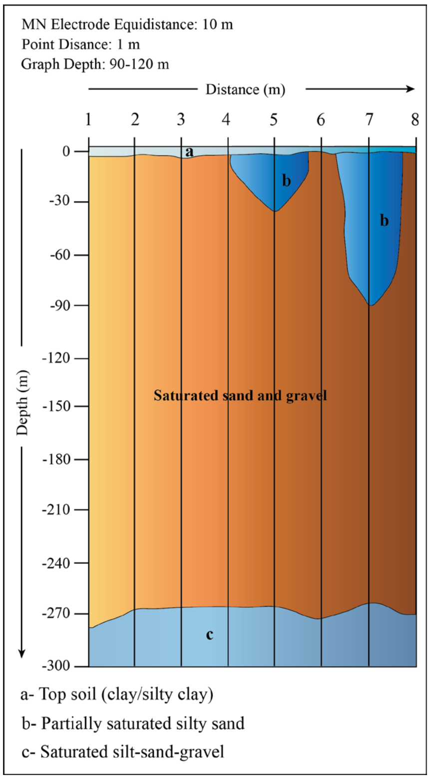

Fig. 17: Lithological Description (Profile-3)

Summary

Profile 1 (Fig. 10 and Fig. 11)

- Anomaly: Low-resistivity zone from 15–60 m depth (Chainage 9 m from start).
- Lithology: Saturated unconsolidated sediments.

Profile 2 (Fig. 13 and Fig. 14)

- Anomaly: Saturated layer from 15–130 m (Chainage 4 m from start).

Profile 3 (Fig. 16 and Fig. 17)

- Anomaly: Saturated zone beneath 15 m depth (Chainage 7 m from start).

Discussions

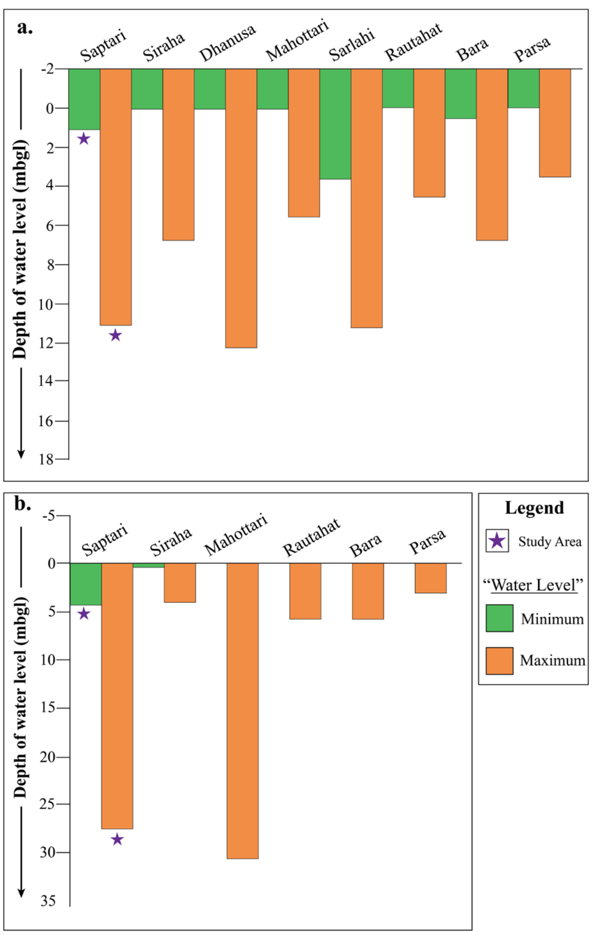

Fig. 18: Water Level Depths (a) Shallow Aquifer and (b) Deep Aquifer (after Shrestha et al., 2018)

The main objective of this study was to identify water bearing zones natural electromagnetic methods. From the iso-resistivity profile map, three sub-surface layers were delineated, namely, unsaturated, partially saturated and unsaturated layers (on the basis of their hydrogeological parameters). All of the three iso-resistivity profiles exhibit a consistent shallow water table occurring between 10 m to 15 m depth as indicated by low electric potential values (<0.3 mV). This depth correlates with the nearby borehole logs. Similarly, the study conducted by (Shrestha et al., 2018) indicates that the water level depths in Saptari District for shallow aquifer varies from 1 m to 11 m and 5 m to 27 m for deep aquifers (Fig. 18). However, to optimize well yield and to enhance hydraulic efficiency, recommended drilling depths were selected based on the presence of coarse-grained, saturated layer present at variable depth of 50 m to 120 m within the aquifer system. The transmissivity varies from 15 m^2/day to 8000 m^2/day (Fig. 19). These layers, interpreted as fluvial sand and gravel deposit reflects the heterogeneous nature (both vertical and lateral heterogeneity) of fluvial depositional system. Prioritizing these high-permeable zones for screen installation ensures sustainable groundwater extraction by minimizing drawdown and maximizing well efficiency.

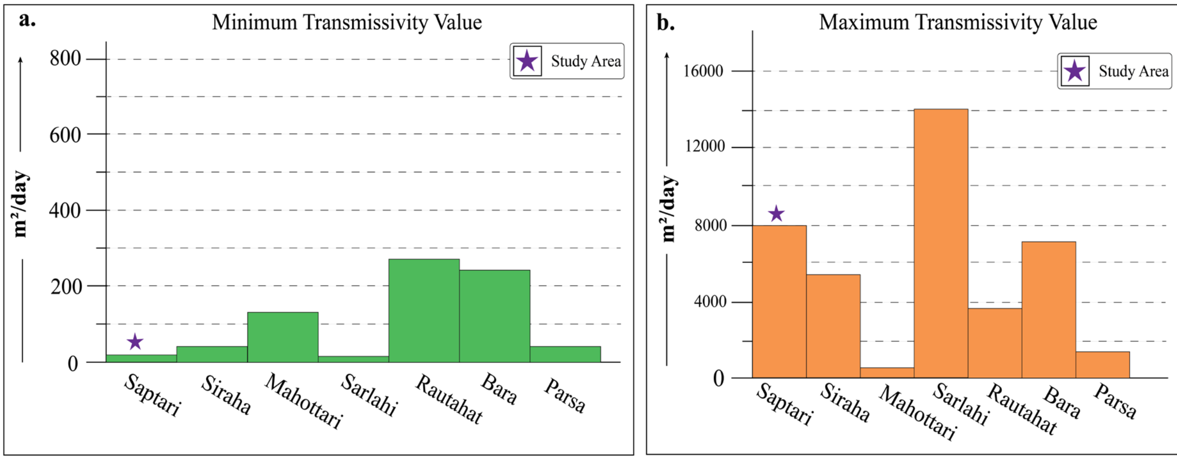

Fig. 19: Minimum and Maximum Transmissivity (after Shrestha et al., 2018)

Likely, many national and international researchers have worked in assessing the quality and quantity of groundwater potential in the Nepal Himalaya using non-invasive geophysical approaches. Shallow aquifer potential mapping was carried out by Thapa et al. (2019) where they conducted five 2D Electrical Resistivity Tomography surveys in Saptari District. They found out variation in lithological formation, including a patchwork of clay, silty clay, sand, gravel and boulder materials, with varying groundwater table (5-15 m depth). The findings of the present study show close resemblance in context of depth of water table and lithological composition. Similarly, Gautam et al. (2000) mapped subsurface karst structure with gamma ray and electrical resistivity profiles in Pokhara valley and inferred network of three linear subsurface channels orienting in NNE-SSW directions. Shah and Shrestha (2017) conducted geo-electrical sounding survey in the various part of the Lekhnath area of Pokhara Valley, Kaski District and determined aquifer thickness varying from 34 m to more than 200 m. The average calculated porosity of the aquifer material was 17.32%.

AQUIFER CHARACTERISTICS

A study by Pathak (2016) in Siwalik foothills of east Nepal revealed groundwater table to be deep at the Bhabar Zone, while the aquifer nearby the river and in Middle Terai is relatively shallow. Interpretation of iso-resistivity profile revealed the present study area to constitute mixed lithological composition, characteristic of both the Bhabar zone (gravel-boulders) and Middle Terai (silt-clay-sand-gravels). Also, the mapped aquifers (40–130 m depth) align with the hydrogeology of the Bhabar Zone, where coarse sediments enable deep percolation. Shallow aquifers (Profile 1) may represent local perched layers, while deeper zones (Profiles 2, 3) correlate with regional unconfined aquifers. Yield variations may be subjected to heterogeneity in sediment porosity and connectivity.

TECHNIQUE EFFICACY

The NEF method rapidly identified water-bearing zones with high resolution (1 m spacing). Its advantages include:

- **Cost-effectiveness:** Eliminates artificial power sources (Paterson and Ronka, 1971).
- **Speed:** 150 m profiles surveyed in <4 hours. However, depth limitations (max 150 m) restrict mapping of deeper aquifers in the Terai, which can extend to 500 m (Sah and Shrestha, 2007). Anomalies also require validation via pumping tests to confirm yield estimates.

SOCIOECONOMIC IMPLICATIONS

Use of non-invasive Natural Electromagnetic Field (NEF) technique for aquifer mapping provides significant socio-economic benefits, especially reducing the cost associated with groundwater exploration in resource-constrained regions. Drilling of unsuccessful borehole possesses great financial loss for communities, private sectors and government. Accurate identification of productive aquifer zones before drilling, reduces the unnecessary risk and expenditure. In the present scenario, delineation of saturated zones at different depths provides a clear target for drilling, hence minimizing the risk of failure. This pre-drilling understanding of the sub-surface allows for optimized well and screen placement resulting in time and cost effectiveness. This approach not only saves cost and time but also aids in sustainable water resource management and enhances overall agricultural productivity.

Comparison with Regional Studies

- Very Low Frequency-Electro Magnetic surveys in Nepal's Terai consistently identify low-resistivity layers at 30–150 m (Sharma and Baranwal, 2005). This study's results corroborate Sah et al. (2002), highlighting the Bhabar Zone's role as a recharge corridor where rivers lose their water while passing through these areas. The Middle Terai represents marshy area with shallow groundwater depth and presence of artesian condition.

Conclusion

The Natural Electromagnetic Field technique efficiently delineates shallow aquifer units within the study area:

1. Three productive aquifers were mapped at 40–50 m, 90–120 m, and 110–130 m depths in Rajbiraj.
2. The method provides rapid, low-cost reconnaissance for drilling site selection but requires supplementary pumping tests for yield verification.
3. Future work should integrate seismic or ERT methods to resolve deeper structures and quantify anisotropy.

This approach supports sustainable groundwater management in the Terai, where aquifer resilience is threatened by climate variability and over-extraction (Molle et al., 2018).

Acknowledgement

The authors would like to express their gratitude to the peoples of Rajbiraj Municipality-09 and all other helping hands.

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