

Integration of ERT and Borehole Data for Groundwater Exploration in Kaligandaki River Terrace Deposits Western Nepal Gandaki Province

Khomendra Bhandari

bhandarikhomendra@gmail.com

Tribhuvan University

Research Article

Keywords: Electrical Resistivity Tomography, groundwater exploration, borehole investigation, river-terrace aquifer, alluvial deposits

Posted Date: October 22nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11223580/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Integration of ERT and Borehole Data for Groundwater Exploration in Kaligandaki River Terrace Deposits Western Nepal Gandaki Province

Khomendra Bhandari^{*1}

¹ Tribhuvan University, Tri-chandra Multiple Campus, Department of Geology, Kathmandu, Nepal.

ORCID  <https://orcid.org/0009-0006-6168-3484> (Khomendra Bhandari)

Corresponding Author: Khomendra Bhandari

Email: bhandarikhomendra@gmail.com

Abstract:

Groundwater is an important water resource in the river-terrace environments of the Himalayan region where the strong lithological heterogeneities make the occurrence of groundwater difficult to delineate from surface observations alone. The Khuturkegat/Maldhunga area of Baglung Municipality, Nepal was studied for its groundwater potential by using an integrated approach of Electrical Resistivity Tomography (ERT) and borehole investigation. The ERT survey was carried out to characterize the subsurface resistivity variations and to identify the possible water bearing formations while the borehole drilling gave direct lithological and ground water observations for validation. The ERT interpretation revealed four dominant subsurface zones ranging from relatively unsaturated near-surface alluvial deposits to deeper moisture bearing and saturated formations. Field observations from the boreholes revealed nearly five lithological layers and a progressive increase in moisture content with depth. At approximately 33 m, noticeable groundwater inflow was observed, and between 43 m and 48 m, relatively clear and fresh groundwater was retrieved. The interval was identified as the most promising groundwater-bearing zone. The ERT and borehole observations generally agree confirming the utility of ERT for preliminary aquifer delineation, although a vertical variation of ~4–7 m was observed between some interpreted boundaries. The deviation is due to the different measurement principles and the spatial resolution of the two methods. The results show that the river-terrace aquifer is heterogeneous and is likely recharged by precipitation-induced infiltration and hydraulic interaction with the Kali Gandaki river. The integrated approach provides a practical base for groundwater exploration and sustainable water-resource development in similar alluvial environments of the Himalayas.

Keywords: Electrical Resistivity Tomography, groundwater exploration, borehole investigation, river-terrace aquifer, alluvial deposits

1. Introduction

Ground water is one of the most reliable sources of fresh water for human consumption, agriculture and ecosystem sustainability. Groundwater is essential for the lives and livelihoods of close to two billion people globally (Misi et al., 2018). Groundwater levels in each groundwater system are observed and measured primarily through monitoring wells (Taylor & Alley, 2002). Sustainable groundwater management requires regular monitoring of groundwater levels (Grieff and Hayashi, 2007). The diverse lithology of Nepal's Himalayan aquifer systems, which range from alluvium to high-grade metamorphic rocks, makes them complex (Dhital, 2015). Globally, rising population pressures, rapid urbanization and climate variability have increased demand on groundwater resources, often beyond natural rates of recharge. According to reports from the United Nations (UN) and the World Bank, almost half of the world's population relies on groundwater for drinking, but many areas are seeing a steady decline in both quantity and quality. This ever growing imbalance points towards the need for efficient and scientifically based techniques for groundwater exploration and management. In the context of Nepal, groundwater resources play a crucial role, particularly in regions where surface water availability is highly seasonal. While the

Terai plains have relatively well-studied aquifer systems, the mid-hill and mountainous regions remain less explored and more vulnerable. Recent studies, including those by the International Centre for Integrated Mountain Development (ICIMOD), indicate that springs and shallow groundwater sources in the Himalayan region are drying up at an alarming rate. This trend is largely attributed to changing precipitation patterns, reduced snowmelt contribution (Bhandari et al.), and increasing evapotranspiration linked to climate change. In many hill communities, traditional water sources such as springs and streams are no longer reliable, leading to acute drinking water shortages and increased socio-economic stress. River terrace deposits are common geomorphological features along many river valleys in Nepal and represent a promising but underutilized groundwater resource. These terraces are usually made up of unconsolidated to semi-consolidated alluvial materials like sand, gravel, and silt, which can be potential aquifers. However, the heterogeneity of these deposits limits the use of the conventional methods alone to delineate accurately the groundwater bearing zones. In such environments, indiscriminate or ill-informed drilling often results in unsuccessful wells, leading to economic losses and inefficient use of resources. To overcome these problems, geophysical methods like Electrical Resistivity Tomography (ERT) have gained increased popularity in groundwater exploration. Electrical Resistivity Tomography (ERT) has been widely utilized to map aquifer formations due to its ability to identify subsurface resistivity changes (Hussein et al., 2023). Electrical resistivity tomography is a suitable method for aquifer detection in complex geological settings (Wahab et al. 2021). Electrical resistivity tomography is an effective method for groundwater prospecting in flysch lithology (Żogała et al., 2026). ERT is a non-destructive technique that measures variation in subsurface resistivity that can be correlated to lithology and moisture content. Low resistivity zones are often indications of saturated materials while high resistivity may correlate to dry or compact formations. Combining electrical resistivity tomography with lithological data improves aquifer delineation in alluvial environments (Singh et al., 2024). Electrical resistivity tomography is one of the techniques used in the investigation of groundwater for the detection of resistivity contrasts in the subsurface (Rai, 2020). The efficiency of ERT in delineating aquifer zones, especially under complex geological conditions, has been demonstrated in several studies (e.g., Reynolds J. M., 2011; Loke M. H., 2004). However, ERT interpretation is subject to uncertainties due to factors such as clay content, salinity variations and resolution limitations, despite its advantages. This creates a critical need to integrate ERT data with borehole drilling and lithological logs for the validation and refinement of subsurface interpretations. Borehole logging is an important source of information for aquifer characterization and hydrogeological interpretation (Williams and Paillet, 2023). Jimoh et al. (2018), showed the application of geophysical logs for hydrogeological studies and borehole design. Geophysical borehole logging improves the accuracy of driller's records and helps in lithological validation in hydrogeological studies (Agyekum et al., 2013). Borehole data offer direct ground-truth information about the subsurface such as lithology, depth to the water table, and aquifer properties. The combined application of ERT and borehole data thus increases the confidence and accuracy of groundwater exploration and reduces the chance of drilling failures, thus enabling better decision making. Integrated hydro geophysical approaches have been extensively used in many parts of the world, but their application in the river terrace environments of Nepal, particularly in the hill regions, is still limited. Most of the existing studies deal with either geophysical surveys or borehole analysis separately without proper integration of the two datasets. Furthermore, there has been a lack of site-specific studies that address the unique hydrogeological conditions of river terraces in mountainous terrains and their implications for sustainable water supply under changing climatic conditions. This gap emphasizes the need for comprehensive and integrated studies that enhance scientific understanding and offer practical solutions for water resource management. The present study aims to bridge this gap by integrating Electrical Resistivity Tomography (ERT) with borehole drilling data to investigate groundwater potential in river terrace deposits. The specific objectives of this research are: (i) to delineate subsurface lithological variations and identify potential aquifer zones using ERT, (ii) to validate geophysical interpretations

through borehole lithology and water level data, (iii) to assess the accuracy and reliability of the integrated approach in groundwater exploration, and (iv) to evaluate the implications of the findings for sustainable groundwater development in river terrace environments of Nepal's hill regions. By combining scientific rigor with practical relevance, this study contributes to the development of cost-effective and reliable groundwater exploration strategies. It also provides insights into addressing water scarcity challenges in climate-sensitive mountainous regions, thereby supporting long-term water security and community resilience.

2. Study Area

The study area is located in the Baglung District of the Gandaki Province in Western Nepal. It is bounded by $28^{\circ}15'23.08''\text{N}$ to $28^{\circ}15'27.37''\text{N}$ North latitudes and $83^{\circ}36'57.83''\text{E}$ to $83^{\circ}36'54.00''\text{E}$ in the study area more than 200 m thick quaternary alluvial deposits of river terrace are present. Highly compacted and consolidated sediments from the alluvial terraces of the Kali Gandaki River. The terraces depict an outstanding and spectacular view. The deposits comprise fine matrix to huge boulders of the Lesser, Greater, and Tethys Himalayan rocks. The clasts of marble, gneiss, granite, schist, phyllite, quartzites are present in the area. Highly cemented clast with calcite matrix is present in most of the part of the old alluvial deposits and they are and more than 80 m thick deposits are present. Most part of the upper terrace is weathered and eroded. Most of the plain land in the study area is occupied by the terraces and are being used for agricultural purpose. The top part of the terrace is used for settlements. The river terraces along the Kali Gandaki River are highly distinctive due to their formation in one of the most tectonically active and deeply incised Himalayan valleys. These terraces represent a sequence of former floodplain levels were abandoned as the river progressively incised into its valley during continued Himalayan uplift. This step-like terrace system is particularly well preserved in the Kali Gandaki corridor because of the river's high erosional power and rapid vertical down-cutting. Unlike many lowland river systems, the terraces here are composed of heterogeneous and poorly sorted alluvial deposits, including boulders, cobbles, gravel, sand, and silt. This variation reflects fluctuating energy conditions of past river stages, strongly influenced by monsoonal discharge and tectonic uplift. The presence of multiple terrace levels indicates repeated phases of climatic variation and base-level change, making the system a valuable archive of paleo-hydrological and tectonic history. Figure 1. Electrical Resistivity Tomography (ERT) survey alignment along the investigation profile, extending from chainage 0 m to 360 m.



Figure 1: Red line show the Electrical Resistivity Tomography (ERT) survey alignment and blue point is bore hole drilling area of ground water exploration

The study area gets about 1,060 to 1,150 mm of rain a year, mostly during the monsoon season (June to September). The Department of Hydrology and Meteorology's (DHM 2020) records and regional climatological data show that the South Asian monsoon has a big effect on rainfall in this area. Figure 2. Location of the study area and groundwater exploration site within the investigated river-terrace environment

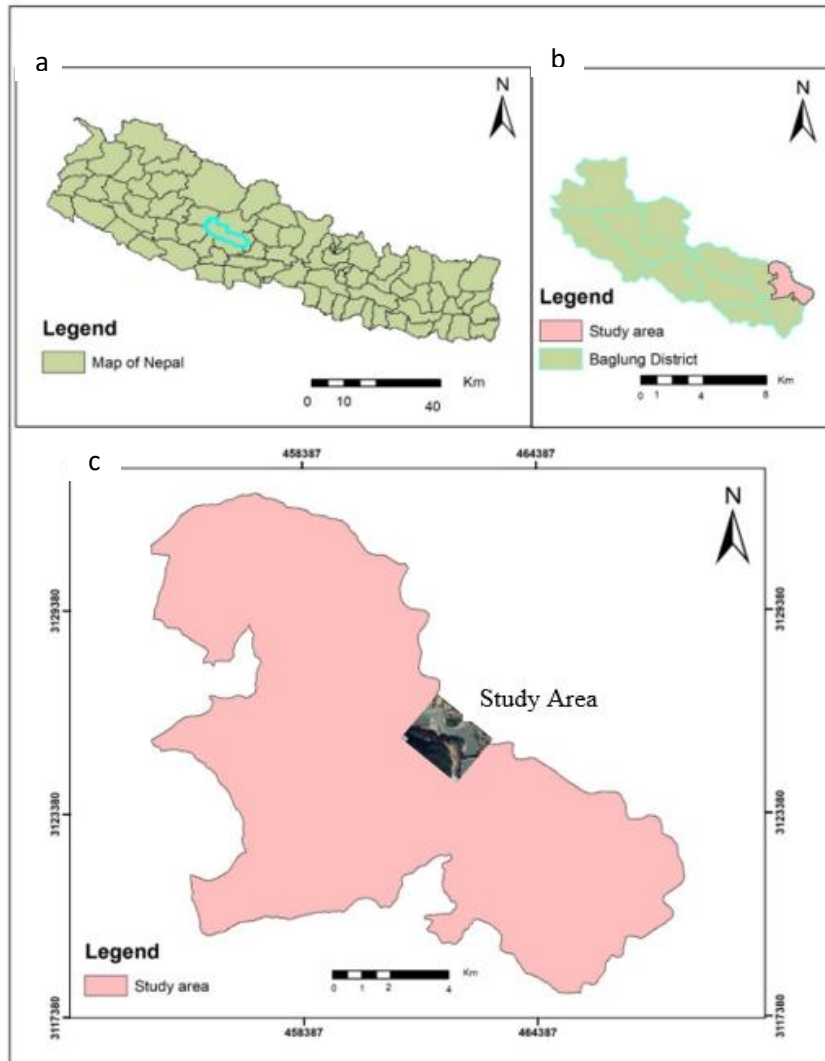


Figure 2: Geographical Setting of the Study Area; (a) Administrative Map of Nepal Showing District Boundaries; (b) Map showing the study area within the corresponding district, with the study area highlighted in pink and the district boundary delineated in green; (c) Detailed location of the groundwater exploration site within the study area, with an inset photograph showing the investigated field site.

The most rain falls in July and August. The hydrogeological setting of the Kali Gandaki River in the study area lies within the tectonically active Lesser Himalayan region of central Nepal. The area is characterized by complex geology, steep terrain, and strong interactions between surface water and groundwater systems. The geology of the area is mostly made up of metamorphic rocks like schist, phyllite, quartzite, and carbonate formations. These rocks have very little primary porosity, so secondary features like fractures, joints, and faults that formed because of strong tectonic activity mostly control where groundwater is found.

These kinds of structural breaks make it easier for water to flow through and serve as pathways for groundwater to move (Kafle, 1996). The Kali Gandaki River has carved out a deep valley with well-developed river terraces. The main aquifer systems in the area are these terraces, which are made up of loose Quaternary deposits like sand, gravel, cobbles, and boulders. These alluvial deposits hold a lot of groundwater because they are very porous and permeable (Lamsal et al., 2018). Monsoonal rain has a big effect on the system's hydrology because it is the main source of groundwater recharge. The river behaves in a dynamic way, acting as both a gaining and losing stream depending on the time of year. In the dry season, groundwater adds to the river's base flow, and in the monsoon, high river discharge helps recharge nearby aquifers by allowing water to seep through the banks (Bookhagen, 2012). The hydrogeological system around Muldhunga is mostly heterogeneous and structurally controlled. The availability of groundwater depends a lot on where alluvial deposits and fractured bedrock are located. This setting shows how important it is to use both hydrogeological and geophysical methods together to get a good picture of groundwater and manage resources in a way that will last. The river originates in the high Himalayan region near the Damodar Himal in Mustang District and flows southward through the central Himalayas. It eventually enters the lowland regions of Nepal and continues into India. One of its most remarkable geomorphological features is the Kali Gandaki Gorge, which lies between the Dhaulagiri and Annapurna mountain ranges. This gorge is recognized as one of the deepest in the world and is a classic example of strong fluvial incision in an active tectonic environment.

Geomorphologically, the Kali Gandaki River exhibits diverse landforms shaped by continuous erosion, deposition, and tectonic uplift. The river valley is characterized by steep V-shaped valleys, indicating dominant vertical down-cutting by the river. Along its course, well-developed river terraces are present, representing former floodplain levels and past stages of river incision. These terraces are often composed of unconsolidated alluvial materials such as sand, gravel, cobbles, and boulders, which play a significant role in groundwater storage and aquifer formation. The river also shows active zones of erosion and deposition, reflecting ongoing landscape evolution influenced by seasonal discharge variations and monsoonal rainfall. The Kali Gandaki River is considered a classic example of an antecedent river, as it maintained its original course while the Himalayas were uplifting, cutting deeply into the rising terrain and forming its present-day gorge.

Overall, the geomorphology of the Kali Gandaki River is highly dynamic and structurally controlled. It is shaped by the interaction of tectonic uplift, climatic factors, and fluvial processes. This makes the river system highly significant for studies in geomorphology, hydrogeology, sediment dynamics, and environmental management.

3. Methodology

3.1 Electrical Resistivity Tomography (ERT) Survey

The methodology of the study consists of materials collection; literature collection and review, geological observation and geophysical (ERT) survey, data computation, processing and interpretation; and finally investigation. Electrical Resistivity Tomography (ERT) surveys were conducted using four electrodes: two current electrodes (C1, C2) and two potential electrodes (P1, P2) show in figure 3. Different electrode configurations were considered based on their suitability for subsurface investigation. Among the commonly used arrays, Wenner, Schlumberger, and Dipole–Dipole were evaluated in terms of signal strength, resolution, and field applicability. The Wenner array provides a high signal-to-noise ratio (SNR), good lateral and vertical resolution, and produces symmetrical anomaly patterns, making it reliable for groundwater investigations. Schlumberger and Dipole–Dipole arrays are effective in detecting lateral variations and were used for cross-verification of subsurface conditions. The survey employed multi-core cables with fixed electrode spacing and an automatic switching system, enabling efficient data acquisition without repeatedly moving electrodes. Electrical Resistivity Tomography (ERT) is commonly used in

groundwater exploration and hydrological studies (Andrade, 2011). Electrical Resistivity Tomography (ERT) represents a powerful tool for mapping soil–rock interfaces and for understanding subsurface heterogeneity in karstic environments (Cheng et al., 2019). The Electrical Resistivity Tomogram (ERT) with Wenner and Dipole-Dipole array was conducted with Geomative GD-10 while Schlumberger arrays was applied for verification and improved interpretation of subsurface conditions. Other accessories that were used during the study were District Map, GPS (Global Positioning System), Photographic Camera, Brunton Compass etc. Literatures and information related to topography, climate, geology, and socio-economic condition of the area was collected and reviewed.

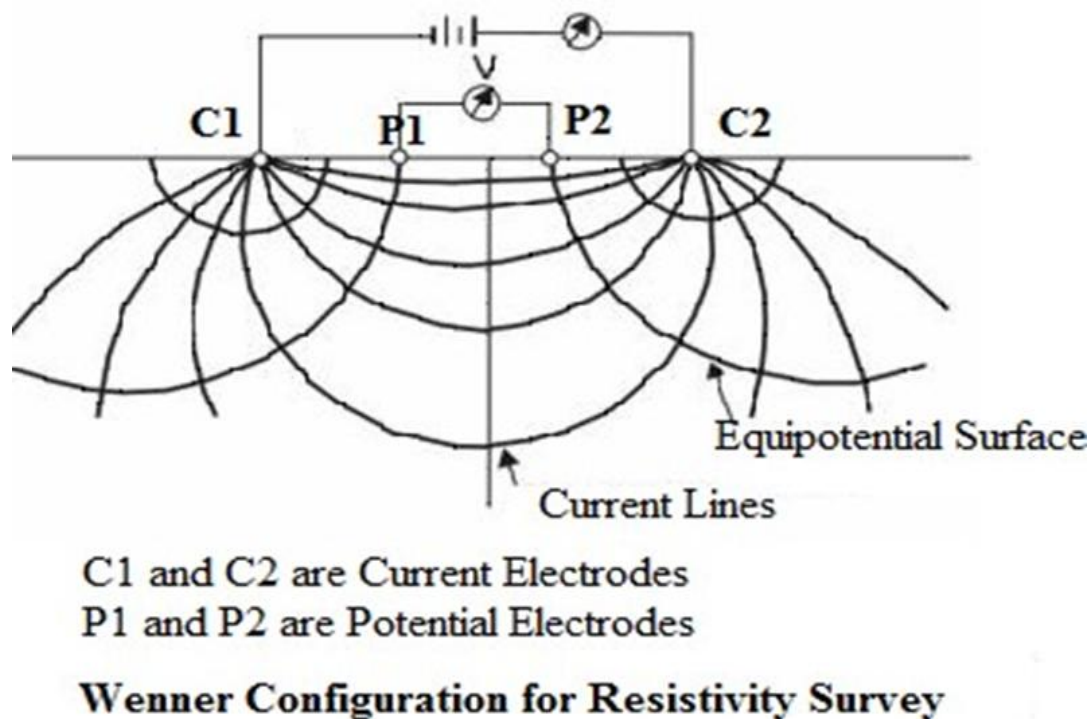


Figure 3: Schematic representation of the Wenner electrode array showing electrode arrangement, current injection, potential measurement, and the corresponding resistivity survey procedure.

Resistivity Meter (Geomative GD-10) was used for electrical resistivity tomogram (ERT) data collection. GPS was used to take spot location of the observation point (ERT Profile) and other important features like dug wells, tube wells water body etc. Photograph were taken do characterized the topographical and morphological character of the area. The general geology, hydrogeology of the area was taken from the geological map, hydrogeological map of the area prepared by Department of Mines and Geology (DMG). Figure 4 Schematic illustration of the Wenner electrode array and resistivity data-acquisition procedure, showing the current electrodes (C_1 , C_2), potential electrodes (P_1 , P_2), electrode spacing (a), measurement stations, data levels (n), and connection of the resistivity meter to the data-processing computer. Progressive expansion of the Wenner electrode array increases the effective depth of investigation, while successive measurements along the profile provide information on the lateral and vertical distribution of subsurface electrical resistivity.

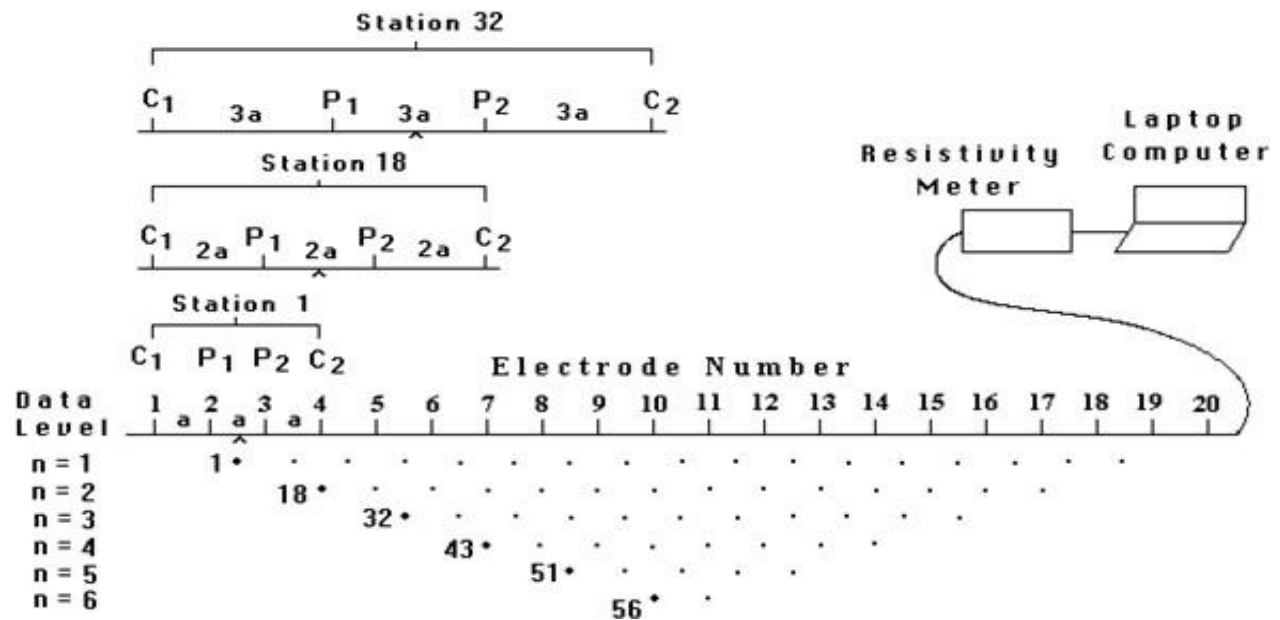


Figure 4: In the Wenner configuration, current is injected into the subsurface through the outer electrodes (C_1 and C_2), while the resulting potential difference is measured between the inner electrodes (P_1 and P_2). The electrode array is systematically moved and expanded along the survey profile to acquire apparent-resistivity measurements at progressively greater investigation depths. The description of the geology of the area was done from the published and unpublished literatures and verified in the field by observation and field measurement

3.2 Borehole Drilling lithology data

Borehole drilling and logging is a fundamental investigative technique widely used in hydrogeology, geotechnical engineering, and environmental studies to understand subsurface conditions. Borehole logging provides reliable subsurface information (Freeze & Cherry, 1979). It involves the systematic drilling of a borehole into the ground and the continuous recording of geological and hydrogeological information obtained from drilling cuttings, core samples, and in-situ observations (Agyekum et al., 2013). One of the primary parameters recorded during borehole investigations is depth, which refers to the vertical distance measured from the ground surface to a specific point within the borehole. Depth is typically expressed in meters and serves as the fundamental reference for correlating all subsurface data. It allows the identification of different stratigraphic layers and their thicknesses, which is essential for understanding subsurface geological variability and for engineering design applications such as foundation planning and groundwater development. A second critical component of borehole logging is the lithology log. This is a detailed descriptive record of the subsurface materials encountered at different depth intervals. The lithology log typically includes information on soil or rock type, color, grain size, texture, degree of compaction or hardness, moisture condition, and weathering characteristics. For example, a borehole may reveal an upper layer of loose silty sand, underlain by medium to coarse sand, and followed by stiff clay or bedrock. Lithological logging is essential for interpreting depositional environments, identifying aquifer

and aquitard zones, and developing geological and hydrogeological models of the study area. It also provides critical input for groundwater resource assessment and engineering feasibility studies. Another important parameter recorded during borehole drilling is the water strike level, which refers to the depth at which groundwater is first encountered during drilling operations. This is typically observed when water begins to enter the borehole from permeable formations. In many cases, multiple water strikes may be recorded at different depths, indicating the presence of layered aquifer systems. The water strike level is crucial for determining groundwater availability, aquifer depth, and hydraulic properties of subsurface formations. It also plays a key role in the design and construction of water supply wells, as well as in sustainable groundwater management. Overall, borehole drilling and logging, through the integration of depth measurement, lithological description, and water strike identification, provides a comprehensive understanding of subsurface conditions necessary for both scientific research and practical engineering applications.

3.3 Data Integration Method

The main strength of this study is the integration of geophysical and geological data which enhances the reliability and accuracy of interpretation of the subsurface. In this study, ERT data were always integrated with borehole lithological records to establish a consistent correlation between resistivity values and the subsurface geological formations. Resistivity data obtained from ERT surveys are indirect indicators of the subsurface conditions and have to be calibrated with direct observations from borehole logs. In this study resistivity ranges were correlated with the lithological units observed during borehole drilling. Low resistivity values are generally associated with clay-rich or moist fine-grained materials because of the higher moisture content and ionic conductivity, whereas moderate resistivity values are generally indicative of sandy or silty formations. Generally, high resistivity zones correspond to coarse grained materials such as gravels, boulders or compact bedrock with low water content. A site-specific correlation between resistivity and lithology was obtained by correlating the borehole depth profiles with the resistivity sections. This correlation reduces the ambiguity for the geophysical interpretation and permits a better definition of the aquifer, impervious layers and transition zones. The systematic study of the borehole lithological data was performed ensuring a proper depth control, regular sampling intervals and detailed characterization of the recovered materials. Each sample was assigned to its corresponding depth interval and evaluated for lithology, grain size, texture, composition, degree of weathering, sorting, and the relative proportion of coarse- and fine-grained material. Accurate sample depth referencing is important as differences between sample depth and lithological boundaries can lead to incorrect correlation with geophysical models and therefore affect the interpretation of subsurface hydrogeological conditions. So the interpreted lithological units were presented by their real depth intervals and correlated with the resistivity distribution obtained from ERT to identify the correlation between the subsurface materials and electrical responses. Such an integrated interpretation is especially important in alluvial environments where clay, silt, sand, gravel and conglomeratic deposits can exhibit different resistivity values depending on lithology, porosity, moisture content and groundwater saturation (Dahlin and Zhou, 2004). The borehole information gives direct geological ground-truth for evaluation of the ERT interpretation, while the ERT model provides spatial continuity between borehole-controlled lithological units, leading to a more reliable interpretation of the subsurface lithology and potential aquifer zones (Dahlin and Zhou, 2004, Binley & Kemna, 2005).

4. Geological setting of the study area

The study area is located in the Lesser Himalayan metasedimentary succession of the Kusma–Baglung region, western Nepal. The Quaternary fluvial and river-terrace deposits of the Kali Gandaki River locally overlie the Precambrian metamorphic rocks. The regional geology is dominated by phyllite, quartzite, metasandstone and other metasedimentary lithology of the Lesser Himalayan sequence (including units of the Kuncha Formation and associated quartzite). The bedrock within the immediate study area is mainly phyllite and quartzite in figure 5. Phyllite is usually fine-grained and foliated, and is characterized by greenish-gray to bluish-gray micaceous features, occasional quartz veins, and interbeds of quartzite and metasandstone. It may provide secondary pathways for the movement of groundwater by virtue of its foliation, weathering, compositional variability, and discontinuities. However, quartzite is relatively

competent and resistant, and occurs as medium- to thick-bedded and locally fractured and jointed rock. Depending upon their connectivity and intensity, such fractures and weathered zones may increase secondary permeability.

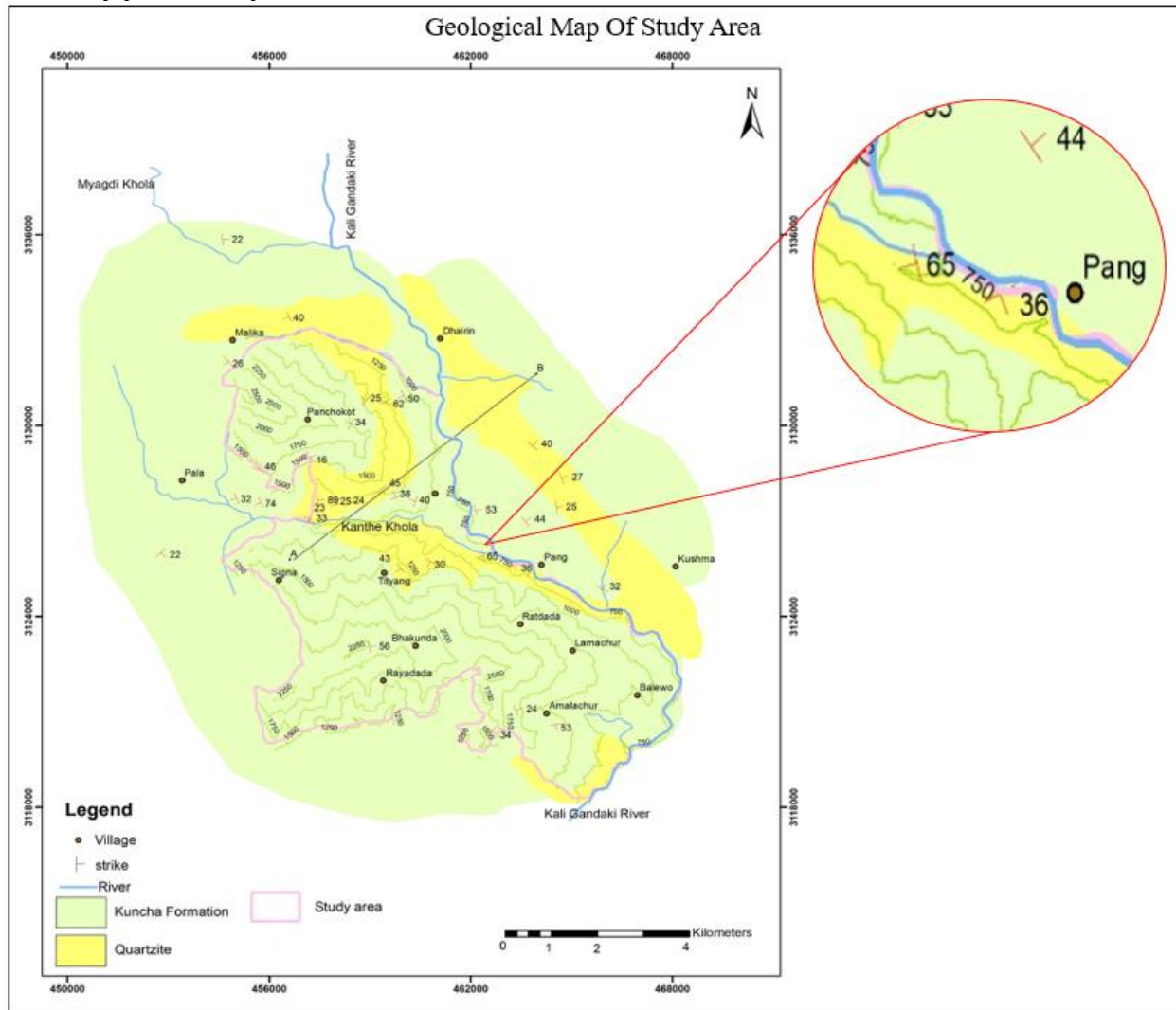


Figure 5: Geological map of the study area showing the spatial distribution of phyllite associated with the Kuncha Formation (green) and quartzite (yellow), with the enlarged circle highlighting the location of the groundwater exploration site within the Kali Gandaki river-terrace deposits

The site for the groundwater investigation lies on Quaternary alluvial- and river-terrace deposits that have been formed along the Kali Gandaki River. These unconsolidated sediments are heterogeneous mixtures of gravel, sand, silt and larger clasts derived from the surrounding and upstream Himalayan lithology of quartzite, phyllite, schist, gneiss, limestone and marble. Their mostly unconsolidated and heterogeneous nature provides good conditions for pore-water storage and groundwater flow compared to the underlying metamorphic bedrock. The geological contrast between fine grained foliated phyllite, competent but fractured quartzite, and unconsolidated alluvial/terrace sediments is also important in interpreting the ERT results, as this lithology and their associated weathering, fracturing, and groundwater conditions can produce significant variations in electrical resistivity. So the resistivity distribution was interpreted on the basis of geological observations, borehole lithology, weathering condition and groundwater occurrence, instead of only resistivity values.

Soil type of study area

The study area is mainly covered by Quaternary alluvial and river-terrace deposits developed along the Kali Gandaki river. These deposits attain locally more than 80 m in thickness and are mainly composed of highly compacted heterogeneous sediments resulting from erosion and transportation of the Himalayan source rocks. The deposits are a mix of gravel, sand, silt and a relatively fine-grained matrix with abundant rock fragments which include schist, phyllite, quartzite, sandstone, limestone, dolomite and other metamorphic and sedimentary lithology. The heterogeneity and large thickness of these deposits provide large pore space and possible pathways for groundwater storage and movement, which make the river-terrace deposits particularly important for groundwater exploration. The relatively flat and elevated terrace surfaces are also largely occupied by agricultural land and human settlements, indicating their geomorphological and socio-economic significance in the study area. Figure 6 Spatial distribution of soil types within the study area

Soil Types of the Study Area

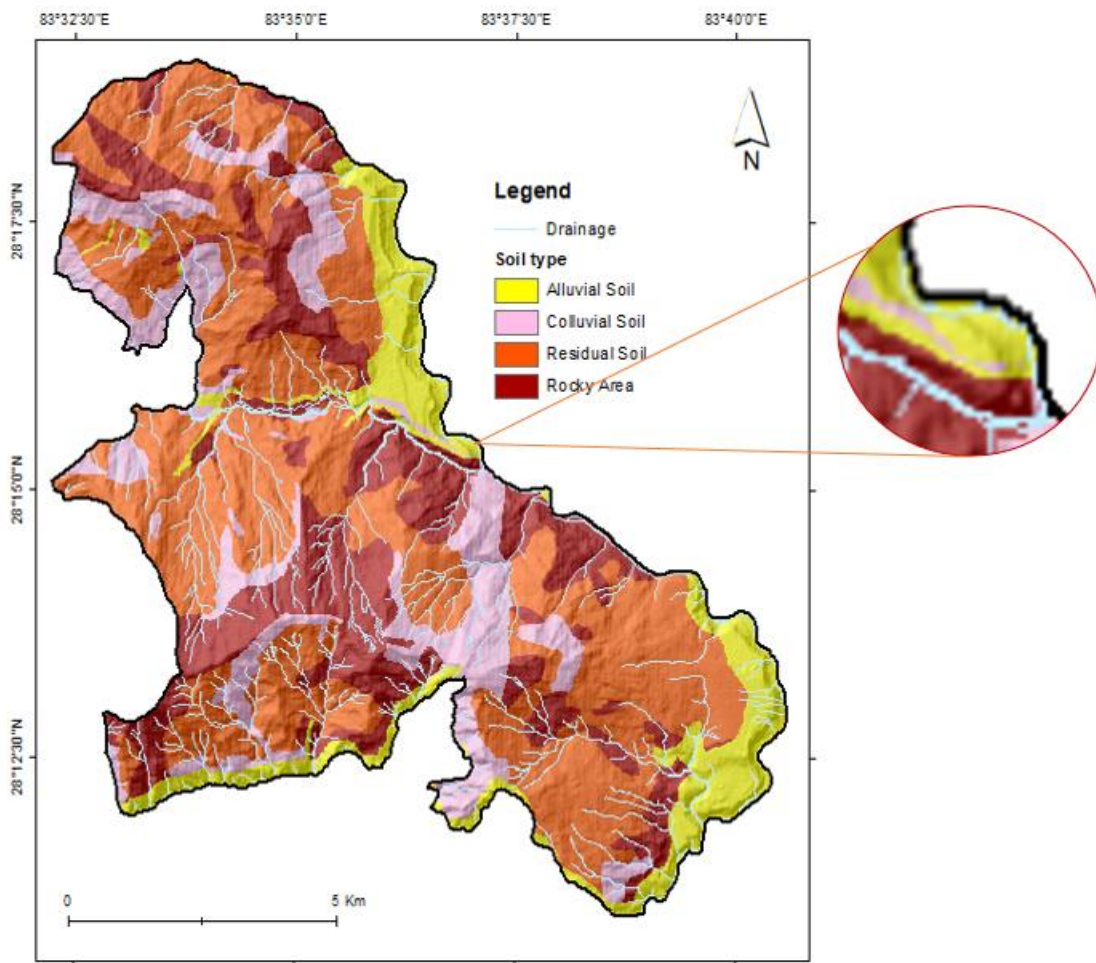


Figure 6: Soil distribution map of the study area, showing the spatial extent of alluvial soils (yellow). (Adapted from Bhandari et al. 2023).

4. Results

4.1 ERT Interpretation

Geo-electrical sounding is a widely used geophysical method for groundwater exploration, environmental studies, and various engineering applications. This method is advantageous because surveys can be conducted rapidly and cost-effectively. Key objectives of an electrical resistivity survey include detecting the water table, identifying variations in resistivity with depth (to distinguish layered earth), and detecting contaminant plumes. Field data were collected and initially processed on-site by an experienced geophysicist to ensure quality. The data were then filtered, analyzed, and interpreted using the software RES2DINV. This software inverts the field measurements, calculates a resistivity model, and generates outputs in the form of resistivity contours. These inversion results are subsequently used to derive lithological and geological information. The relationship between resistivity values and lithology/geology, as discussed in previous sections, was applied for interpretation. The resistivity of a given layer depends on factors such as rock type, grain size, porosity, water content, and degree of weathering. Based on various studies conducted in different parts of Nepal, a general correlation table is provided in Table 1; however, it is important to note that resistivity values for specific lithology can vary widely. In this study, two Electrical Resistivity Tomograms (ERT-1) were conducted to cover the area, using both Wenner and Dipole-Dipole electrode configurations. The survey location is shown in Figure 1. Topographically, the study area consists of gently sloping mountainous terrain with alluvial fan deposits. The inversion results, including resistivity tomograms and interpretative cross-sections for all profiles, are presented in Figures 7 to 8. The interpretative sections reflect the topographic slope, as electrodes were positioned along slope distances rather than horizontal distances. Therefore, although the sections may appear elongated, the actual horizontal distances are shorter. Apparent resistivity values (ρ_a) were plotted against electrode spacing on a log-log scale to produce resistivity curves. These curves, together with the best-fit models, were used to prepare lithological sections. The survey photographs and field curves are presented in the Annex. Resistivity values were quantitatively interpreted to determine lithology and layer thickness, considering that resistivity depends on factors such as rock type, grain size, porosity, water content, and degree of weathering. General correlations based on studies in different parts of Nepal are provided in Table 1

Table 1. Correlation of resistivity and lithology

Resistivity (Ohm-m)	Expected Lithology	
	Unsaturated condition	Saturated condition
< 30		Clay
30- 60	Clay Silt	
60-150	Clayey Sand	Silt coarse sand
60-250	Silt coarse sand	
50-200		Sand and gravel
100-5000	Sand, gravels	
30-100		Coarse sand gravels
700-2000	Coarse sand gravel boulders	
70 -1500		Highly fractured / jointed rocks
500 and above	Fractured rocks / Hard bedrock	

The resistivity values shall be interpreted in terms of lithology and thickness in quantitative analysis. The resistivity of certain layer depends up on rock type, grain size degree of void spaces and amount of water present, degree of weathering etc. Based on different studies carried out in different part of Nepal, the general correlation table is shown in Table 1. Correlation of resistivity and lithology

Imaging and Assessment of Subsurface Geology
Groundwater Potential Survey at Baglung-1, Maldhunga, Laxmi Narayan Mandir Area
Electrical Resistivity Tomogram (ERT-1)

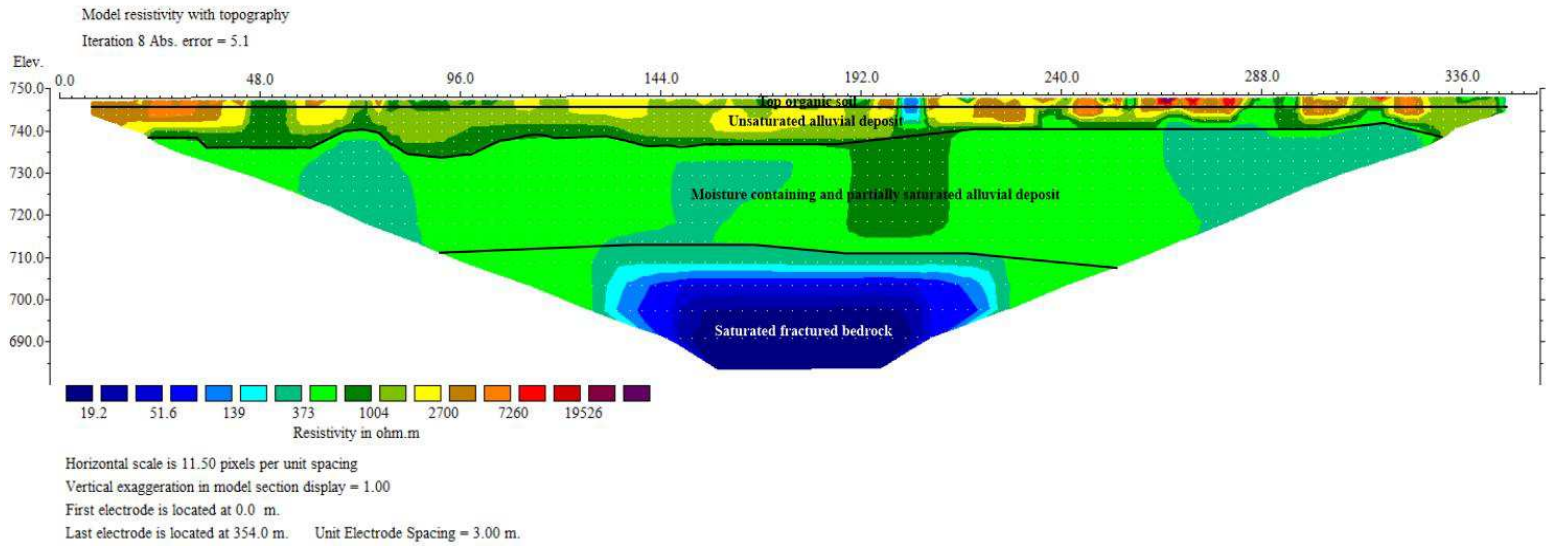


Figure 7: Image revealed by electrical resistivity tomogram survey. vertical axis show the elevation and horizontal line show the chainage 0 m to 336 m

The ERT survey revealed a multi-layered subsurface at the survey site. As shown in Figures 7, the layers consist of top organic soil, unsaturated alluvial deposits, moisture-bearing and partially saturated alluvial deposits, unsaturated fractured bedrock, and saturated fractured bedrock. The top layer, interpreted as organic soil, exhibits resistivity values ranging from very low to very high and has a thickness of approximately 2–3 m. Beneath this, relatively high resistivity materials correspond to unsaturated alluvial deposits, with a thickness of about 8–10 m, consistently observed throughout the survey profile. The next layer, characterized by medium resistivity values, represents moisture-bearing and partially saturated alluvial deposits, with an estimated thickness of 25–30 m. Below a depth of 40–45 m, medium to very low resistivity materials are interpreted as saturated fractured bedrock, which extends beyond the investigation depth.

Imaging and Assessment of Subsurface Geology
Groundwater Potential Survey at Baglung-1, Maldhunga, Laxmi Narayan Mandir Area
Lithological Section of ERT-1

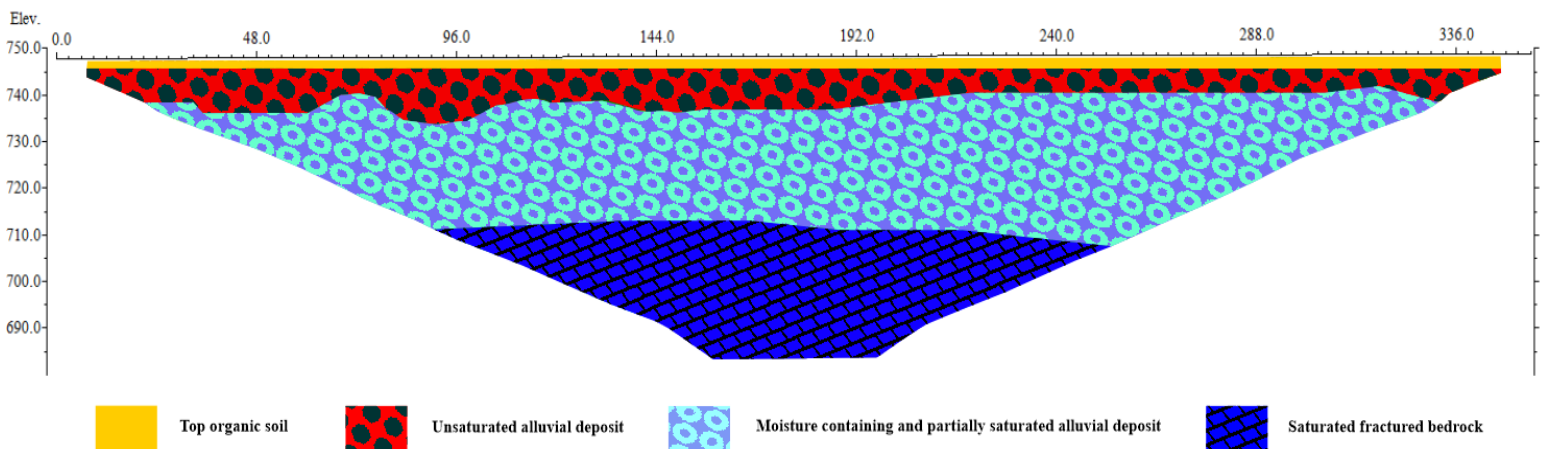


Figure 8: Lithological section of electrical resistivity tomogram survey from first profile (ERT-1)

4.2 Observed lithology from drilling Data

After the ERT survey borehole drilling was performed following the interpreted subsurface resistivity results for the verification of the geophysical interpretation and for the characterization of the subsurface lithology. Samples of subsurface materials were obtained at successive depth intervals during drilling. Each recovered sample was measured, described, and recorded according to its lithology, grain size, texture, degree of compaction, and moisture condition. Depth-specific sample information shown in figure 9.

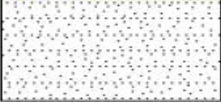
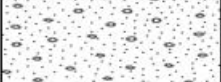
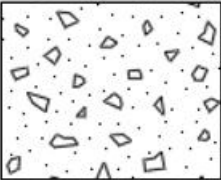
BH 1	From	To	Symbol	Lithology
	0 m	7 m		Top Soil, Organic soil, Clay
	7 m	11 m		Gravel, silty sand
	11 m	20 m		Sandy, Gravel and Pebble
	20 m	43 m		Low saturate Conglomerate low
	43 m	65 m		Highly saturate conglomerate

Figure 9: Depth-wise arrangement of borehole samples and corresponding vertical lithological profile of the subsurface materials.

The BH-1 borehole log, developed from samples collected during drilling, provides direct information on the subsurface lithological sequence and groundwater saturation conditions down to a depth of 65 m. When integrated with the previously obtained ERT profile in Figure 9 this borehole log provides important ground-truth validation of the geophysical interpretation. From 0 m –7 m, the borehole consists of topsoil, organic soil, and clay. This relatively fine-grained unit is expected to have comparatively low hydraulic conductivity and may partially restrict downward infiltration (Freeze and Cherry, 1979). The 7 m–11 m

interval comprises silty sand and gravel, representing a transition toward coarser alluvial material. The presence of gravel increases pore connectivity and may facilitate groundwater infiltration and movement.

From 11 m –20 m, sandy gravel and pebbles dominate. This coarse-grained alluvial unit is expected to possess relatively high permeability and hydraulic conductivity, making it a potentially important recharge and groundwater-bearing zone. The 20 m –43 m interval is characterized by low-saturated conglomerate. Although the coarse clasts may provide considerable pore space, the relatively low degree of saturation indicates limited groundwater filling within the pore network at the time of investigation. In contrast, the 43 m –65 m interval consists of highly saturated conglomerate, indicating substantial groundwater occurrence within the formation. The coarse-grained nature and high saturation suggest that this interval may represent the principal groundwater-bearing aquifer zone encountered in BH-1. Overall, the borehole demonstrates a vertical transition from fine-grained surface deposits to progressively coarser and more saturated alluvial–conglomeratic formations, supporting the interpretation of a heterogeneous riverbank alluvial aquifer system.

4.3 Correlation of lithology and resistivity

The borehole investigation provided direct information on subsurface lithology and occurrence of ground water and was used as an independent ground truth reference for evaluating the ERT interpretation. Figure 10. Borehole lithology compared to resistivity profile obtained from ERT, showing the relationship between subsurface lithological units and their resistivity responses.

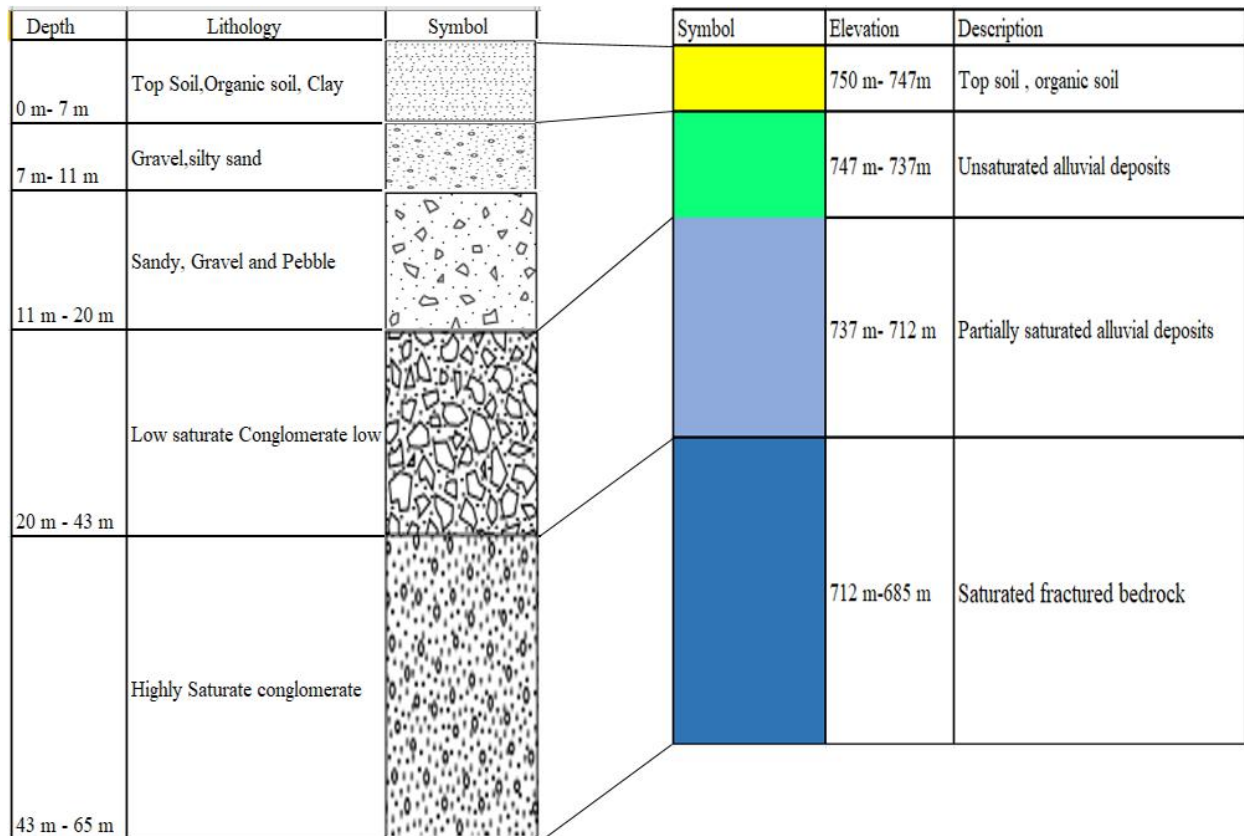


Figure 10: Correlation between lithology and Resistivity data

The analysis of the drilling samples revealed about five different lithological layers in the investigated depth interval. The upper part of the borehole was mostly composed of relatively unsaturated alluvial materials, and a progressively increasing moisture content with depth was observed, suggesting a gradual transition to more water-saturated subsurface materials. A marked increase of groundwater inflow was observed at a depth of about 33 m, which suggests the formation of a more permeable and hydraulically connected water-bearing zone. The best conditions for groundwater were found at a depth between about 43 and 48 m. Here a relatively high yielding zone produced clear and fresh groundwater, indicating the presence of a major saturated and permeable aquifer interval. The borehole observations are in general agreement with the resistivity structure interpreted from the ERT survey. The gradual increase in moisture content and groundwater occurrence with depth is broadly consistent with the transition from relatively higher to lower resistivity zones identified in the ERT section. However, the vertical variation of the boundaries of the interpreted resistivity zones and the corresponding lithological and water-bearing intervals derived from the boreholes is about 4 m to 7 m. This difference should not necessarily be interpreted as an error in either data set as ERT is a two-dimensional, spatially averaged estimate of subsurface electrical resistivity while borehole observations are direct but very localized measurements at a single point. Differences in lithology, porosity, saturation, groundwater distribution, and lateral heterogeneity can therefore result in differences in apparent depth of subsurface boundaries between the two methods.

To summarize, the borehole results provide significant ground-truth support for the ERT interpretation, especially for locating the transition to the saturated alluvial materials and the deeper groundwater-bearing zone. The integrated results show the heterogeneity of the subsurface aquifer system and the strong influence of the distribution of the permeable alluvial layers and the degree of saturation on the occurrence of the ground water

The ERT profile shows four main subsurface resistivity zones due to variation in lithology, moisture content and groundwater saturation degree. The upper resistivity zone is interpreted as relatively unsaturated alluvial material while the lower zones suggest increasing moisture content and saturation. The deeper low-to-moderate resistivity zones are of special interest as they may be water-bearing alluvial sediments with higher pore-water saturation. The geophysical interpretations are in good overall agreement with the borehole observations. The borehole investigation indicated about five lithological layers with a progressive increase in moisture content with depth. Significant inflow of groundwater was recorded at about 33 m. The interval between 43 m and 48 m was characterized by relatively clear and fresh groundwater which indicated a relatively good aquifer zone. This deeper water-bearing interval generally corresponds to the deeper resistivity anomaly seen in the ERT section. The ERT interpreted boundaries differ from those observed in the borehole by about 4 m – 7 m but the general vertical sequence and groundwater occurrence show consistent trends. These differences are expected because ERT is a spatial average of subsurface electrical properties, whereas borehole data are localized direct observations. The correlation thus suggests that the ERT results are generally supported by the borehole data and are able to delineate the heterogeneous alluvial aquifer system.

Accuracy / error

The ERT interpretation was well correlated with borehole observations and thus the subsurface characterization was generally reliable. However, some interpreted layer boundaries showed a vertical difference of about 4 m – 7 m. This difference should be regarded as an intrinsic uncertainty, not as a direct measurement error. The ERT inversion calculates resistivity of the subsurface from electrical measurements taken at different locations in the field, and is therefore affected by electrode spacing, the regularization of the inversion, data noise, and lateral heterogeneity of the lithology. Conversely, borehole data offer direct and localized observation of lithology and groundwater conditions. The observed depth variation may thus be attributed to the different spatial resolution and measurement principles of the two methods. In general, the good agreement in the major subsurface layering and the recognition of the deeper water-bearing zone

suggests that the ERT model provides a reasonable and independently supported depiction of the subsurface aquifer conditions.

5. Discussion

The ERT investigation gives a useful and reasonably reliable characterization of the subsurface hydrogeological conditions in the study area. The interpreted resistivity structure reveals four major subsurface zones including the near surface organic soil, relatively unsaturated alluvial deposits, moisture bearing to partially saturated alluvial deposits and a deeper saturated zone interpreted as fractured bedrock. The gradual trend of relatively resistive materials at the near-surface to lower-to-moderate resistivity at depth is consistent with increasing moisture and groundwater saturation within the subsurface. The borehole data offer additional confirmation for the validity of the ERT inversion. Drilling revealed about five lithological layers and a progressive increase in moisture content with depth. Noteworthy groundwater inflow was encountered at about 33 m depth and relatively clear and fresh groundwater was obtained from about 43 m to 48 m depth. This deeper water-bearing interval broadly corresponds to the deeper conductive to moderately resistive zone identified in the ERT model and provides independent ground-truth support for the geophysical interpretation.

Some ERT derived boundaries showed an average vertical offset of ~4–7 m in comparison to borehole observations. This difference is treated as intrinsic uncertainty linked to the different spatial resolutions and measurement principles of the two methods and not as a direct error. ERT provides a spatially averaged 2D estimate of electrical resistivity; whereas borehole logging and sample observations are highly localized. Thus, lateral variations in lithology, porosity, saturation and distribution of ground water may cause apparent variations in the depth to the interpreted boundaries. However, the agreement in the overall subsurface sequence and the identification of the deeper groundwater-bearing interval indicate that the ERT interpretation is reliable enough for preliminary groundwater targeting purposes.

5.1 Resistivity Features of Zones Containing Water

Groundwater bearing formations are mostly connected to the low to moderate resistivity zones in the alluvial sequence and the deeper saturated fractured zone. Low resistivity usually means higher pore-water saturation, especially in permeable sediments with interconnected pore spaces filled with groundwater. However, resistivity alone cannot differentiate groundwater from clay-rich materials, which can both produce relatively low resistivity responses. The results of the ERT show that the shallow moisture-bearing and partially saturated alluvial deposits are a potential and relatively less reliable groundwater zone. Their variable resistivity and incomplete saturation may mean that groundwater storage and transmission are heterogeneous in space. Conversely, the deeper saturated zone, particularly below about 40 m–45 m, has characteristics that are consistent with a more persistent aquifer. The borehole evidence of fresh and clear groundwater between 43 m and 48 m is strong support to the interpretation of this deeper zone as the principal groundwater bearing interval.

Therefore, resistivity response must be interpreted in conjunction with lithology, groundwater presence and borehole evidence, and not by using a single resistivity threshold as a sole indicator of groundwater.

5.2 Aquifer behavior in river-terrace environment

The groundwater system is heavily dominated by the geomorphological setting of the river terrace and its relation to the Kali Gandaki River. The terrace deposits are believed to be composed of a mixture of sand, gravel, cobbles, boulders and finer sediments deposited under variable fluvial conditions. Such materials may have highly variable porosity and permeability both laterally and vertically, resulting in a heterogeneous aquifer system. The river and precipitation are likely to be important sources of recharge. Recharge of shallow and intermediate groundwater may occur due to infiltration of rainfall and surface runoff through permeable terrace deposits. Hydraulic interaction with the Kali Gandaki River may provide additional recharge or seasonal groundwater-level fluctuations (Sophocleous, 2002, Winter et al., 1998).

The coarser gravel- and cobble-rich horizons are expected to act as preferential pathways for the movement of groundwater, whereas finer-grained or clay-rich horizons may locally restrict vertical flow and produce perched or semi-confined groundwater conditions.

The observed increase in the occurrence of groundwater with depth suggests that the deeper aquifer may be a more persistent groundwater system than the shallow partially saturated deposits. The relatively good quality groundwater encountered at 43 m–48 m may be indicative of the presence of accumulated groundwater in a hydraulically connected permeable zone, possibly associated with coarse alluvial materials and/or fractured bedrock. Thus the river-terrace aquifer can be regarded as a vertically and laterally heterogeneous system, in which the availability of groundwater is strongly dependent on the distribution and connectivity of permeable materials.

5.3 Limitations and Sources of Uncertainty

The ERT interpretation is useful but has several limitations. Secondly, the materials rich in clay can generate low resistivity values similar to those of saturated formations, which may result in false identification of groundwater-bearing zones. Second, the resistivity response is dependent on lithology and saturation, but also on porosity, pore water chemistry, temperature and mineral composition. Therefore, a low resistivity anomaly cannot be interpreted as groundwater without additional geological or borehole information. Also, uncertainty can be caused by electrode spacing, data quality, inversion regularization, topographic effects, and the limited resolution of deeper parts of the ERT model. Resolution typically decreases with depth, and the inversion process can smooth and merge thin geological layers. Moreover, the two-dimensional ERT model may not be sufficient to describe the three-dimensional variations in the heterogeneous river-terrace deposits. Thus the ERT results should be interpreted as a hydro-geophysical interpretation, not necessarily a direct measurement of groundwater quantity or yield. Integration with borehole lithology, groundwater inflow, water quality, pumping-test data, and groundwater-level observations is therefore crucial for validating aquifer productivity and sustainability. The good agreement between the ERT interpretation and borehole data in this study greatly reduces the uncertainty and supports the recognition of the deeper saturated zone as the most promising groundwater target.

6. Conclusion

The integrated ERT and borehole study gave a reliable evaluation of the subsurface hydrogeological conditions and groundwater potential of the study area (Reynolds, 2011, Loke, 2004) at Khuturkegat/Maldhunga, Baglung. The ERT survey revealed four main subsurface resistivity zones indicating a transition from relatively unsaturated near-surface materials to increasingly moisture-bearing and saturated formations with depth (Loke et al., 2013). In general, the borehole observations agreed with the ERT interpretation. Groundwater occurrence increased with depth, and a significant inflow was met at ~33 m. The interval between about 43 and 48 m yielded relatively clear and fresh ground water and is the most promising ground-water zone identified during the investigation. The results suggest that the river-terrace deposits are a heterogeneous aquifer system with the occurrence of groundwater being controlled by the distribution and connectivity of permeable alluvial materials and deeper saturated formations. Important potential sources of recharge identified are the Kali Gandaki River and infiltration induced by precipitation. In some cases, a vertical variation of the order of 4–7 m between ERT and borehole boundaries was observed but the overall correlation was satisfactory.

In practice, the development of groundwater should be targeted to the deeper, better saturated aquifer zone with further investigation including pumping tests, groundwater-level monitoring, water quality assessment and additional boreholes to evaluate the extent, yield, recharge and long-term sustainability of the aquifer.

Abbreviations

ERT= Electrical Resistivity Tomography

UN = United Nation

ICIMOD= International Centre for Integrated Mountain Development

DHM= Department of Hydrology and Meteorology

SNR= Signal-to-noise ratio

GPS = Global Positioning System

DMG = Department of Mines and Geology

RES2DINV = Resistivity 2D Inversion

BH= Borehole

Acknowledgments

The authors would like to thank all of their colleagues who helped with this research. We are grateful to the local community and elders and support of us during this difficult work.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

Funding Declaration:

No specific grant was received for this research from any funding agency in the public, commercial or not-for-profit sectors.

Data Availability Statement:

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Clinical Trial Registration

Not applicable. This study is not a clinical trial.

Ethics, Consent to Participate, and Consent to Publish declarations

Not applicable.

Reference

Misi, A., Gumindoga, W., Hoko, Z., 2018. An assessment of groundwater potential and vulnerability in the Upper Manyame Sub-Catchment of Zimbabwe. Phys. Chem. Earth 105, 72–83.

Alley, W. M., & USGS. (2002). The Importance of Monitoring To Groundwater Management. In Sustainable Management of Groundwater in Mexico. <https://doi.org/10.17226/11875>

Grief, L. A., & Hayashi, M. (2007). Establishing a Rural Groundwater Monitoring Network Using Existing Wells: West Nose Creek Pilot Study, Alberta. *Canadian Water Resources Journal*, 32(4), 303–314. <https://doi.org/10.4296/cwrj3204303>

Dhital, M. R. (2015). *Geology of the Nepal Himalaya: Regional perspective of the classic collided orogen*. Springer.

Bhandari, K., Acharya, M., Belbase, S., Ghmire, A., Shrestha, P., et al. (2025). Impacts of Climate Change on Glacial Lake Formation and GLOF Risks in the Nepal Himalaya (2005-2024): A Geospatial and Statistical Analysis. *Earth Sciences*, 14(6), 261-281. <https://doi.org/10.11648/j.earth.20251406.15>

Hussein, M. A., Ali, M. Y., & Hussein, H. A. (2023). Groundwater Investigation through Electrical Resistivity Tomography in the Galhareri District, Galgaduud Region, Somalia: Insights into Hydrogeological Properties. *Water*, 15(18), 3317. <https://doi.org/10.3390/w15183317>

Wahab, M. A., Atya, M. A., & Abbas, A. M. (2021). Application of electrical resistivity tomography for groundwater exploration in volcanic terrains of Japan. *Geoscience Letters*, 8(1), 1–15. <https://doi.org/10.1186/s40562-021-00188-6>

Żogała, B., Stan-Kłeczek, I. & Waligóra, J. The electrical resistivity tomography as a tool for groundwater prospecting in the flysch lithologies: a case study from Poland. *Acta Geophys.* **74**, 6 (2026). <https://doi.org/10.1007/s11600-025-01746-8>

Singh, R., Patel, M., & Verma, S. (2024). Integration of electrical resistivity tomography and lithological logging for groundwater characterization in alluvial aquifers. *Journal of Applied Geophysics*, 212, 104987

Rai, P., Author2, A. A., & Author3, B. B. (Year). Title of the article. *Journal of Water, Environment and Allied Management*, 1(2), 1–15. <https://doi.org/10.47884/jweam.v1i2pp01-15>

Reynolds, J. M. (2011). *An introduction to applied and environmental geophysics* (2nd ed.). Wiley-Blackwell.

Loke, M. H. (2004). Tutorial: 2-D and 3-D *electrical imaging surveys*. Geotomo Software

Williams, J. H., & Paillet, F. L. (2023). *Geophysical logging for hydrogeology*. The Groundwater Project

Jimoh, R. A., Bankole, O. M., Ahmed, K., et al. (2018). Use of geophysical logs in hydrogeological studies and borehole design: Case study of Apapa coastal area, Nigeria. *Applied Water Science*, 8, 191. <https://doi.org/10.1007/s13201-018-0804-9>

Agyekum, W. A., Agyapong, S. Y., & Fianko, J. R. (2013). *Geophysical borehole logging for control of driller's records: Hydrogeological case study from Ghana*. *Applied Water Science*, 3(2), 491–500. <https://doi.org/10.1007/s13201-013-0097-y>

Department of Hydrology and Meteorology. (2020). Preliminary precipitation summary: Monsoon season (June–September), 2020. *Government of Nepal, Ministry of Energy, Water Resources and Irrigation*.

Kafle, K. N. (1996). Engineering geological study of the Kali Gandaki ‘A’ hydroelectric project area, western Nepal Lesser Himalaya. *Journal of Nepal Geological Society*, 13, 65–71. <https://doi.org/10.3126/jngs.v13i0.32132>

Lamsal, S., Sapkota, N., Bhandari, A., Gyanwali, I., Paudyal, K. R., & Paudel, L. (2018). Geological investigation of river terraces along the Modi Khola valley, Parbat District, western Nepal Lesser Himalaya. *Journal of Nepal Geological Society*, 53, 1–10. <https://doi.org/10.3126/jngs.v53i0.23798>

Bookhagen, B. (2012). Himalayan groundwater. *Nature Geoscience*, 5(2), 97–98. <https://doi.org/10.1038/ngeo1366>

Andrade, R. (2011). Intervention of electrical resistance tomography (ERT) in resolving hydrological problems of a semi-arid granite terrain of Southern India. *Journal of the Geological Society of India*, 78, 337–344. <https://doi.org/10.1007/s12594-011-0100>

Cheng, Q., Tao, M., Chen, X., & Binley, A. (2019). *Evaluation of electrical resistivity tomography (ERT) for mapping the soil–rock interface in karstic environments*. *Environmental Earth Sciences*, 78, 439. Cheng, Q., Tao, M., Chen, X., & Binley, A. (2019). *Evaluation of electrical resistivity tomography (ERT) for mapping the soil–rock interface in karstic environments*. *Environmental Earth Sciences*, 78, 439.

Bhandari, K., Acharya, M., Dhital, M. R., & Shrestha, S. (2023). Landslide susceptibility mapping of West Central Nepal Lesser Himalaya Baglung Municipality, Baglung, Nepal. *American Journal of Applied Scientific Research*, 9(4), 163–173. <https://doi.org/10.11648/j.ajasr.20230904.13>

Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. Prentice-Hall.

Dahlin, T., & Zhou, B. (2004). A numerical comparison of 2D resistivity imaging with 10 electrode arrays. *Geophysical Prospecting*, 52(5), 379–398. <https://doi.org/10.1111/j.1365-2478.2004.00423.x>

Binley, A., & Kemna, A. (2005). DC resistivity and induced polarization methods. In Y. Rubin & S. S. Hubbard (Eds.), *Hydrogeophysics* (pp. 129–156). Springer

Sophocleous, M. (2002). Interactions between groundwater and surface water: The state of the science. *Hydrogeology Journal*, 10, 52–67.

Winter, T. C., Harvey, J. W., Franke, O. L., & Alley, W. M. (1998). *Ground Water and Surface Water: A Single Resource*. U.S. Geological Survey Circular 1139.

Loke, M. H., Chambers, J. E., Rucker, D. F., Kuras, O., & Wilkinson, P. B. (2013). Recent developments in the direct-current geoelectrical imaging method. *Journal of Applied Geophysics*, 95, 135–156. <https://doi.org/10.1016/j.jappgeo.2013.07.017>