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Groundwater Potentiality Assessment of hard-rocks in Southern Saudi Arabia Using Electrical Resistivity Tomography Approach

Abstract

Ten profiles of two-dimensional electrical resistivity tomography (ERT) from five sites in southern Saudi Arabia were used to detect groundwater-bearing zones. The groundwater-bearing zones are shallow, with a depth of 20 m and aerial extension (up to 200 m distance). These aquifers extend into the alluvial deposits while weathered/fractured and/or fresh basement rocks underpin this aquifer. Rainfall recharges these unconfined aquifers, as seen by the rise in water levels along the wadi during the wet season.[4] The southern Saudi Arabia area can be considered a groundwater source with a high potential for artificially increasing recharge by constructing subsurface dams that protect the value of the water in addition to rising water levels in the wadi, or by constructing infiltration basins in the upper parts of the wades to increase the amount of water recharge. Because the southern Saudi lowlands get 300 to 360 mm of annual rainfall, the unconfined aquifer can be quickly replenished by rainfall, making it a promising area for groundwater supply for future planning and urbanization projects in neighboring areas.

Keywords**:** Groundwater-bearing zones, ERT, Remote sensing, DEM, Slope, Southern Saudi Arabia

1. Introduction

Saudi Arabia is a dry region with few surface water resources, hence it is crucial to explore groundwater resources for drinking, irrigation, and other uses. Fractionation processes can have a significant impact on underground groundwater in dry places like Saudi Arabia where precipitation is infrequent and evaporation rates are high. This is valid for alluvium deposits in the kingdom's southern region. Memon et al. (1984) and Jamman (1978) discovered that the main determinants of groundwater salinity in the main wadis in the southern region are rock types and agricultural activities. Groundwater supplies are also impacted by regional geological, morphological, tectonic, and climatic factors. Alluvium Fractures and fills with the majority of the available water in arid areas. Any assessment of a groundwater supply is significantly impacted by geological factors. By connecting surface discharge to the groundwater reservoir, these characteristics make the recharging process easier. The geological depictions, which consist of faults, voids, fissures, fractures, crevices, solution cavities, and other structural geological characteristics, control the recharge process.

The majority of the wades in southern Saudi Arabia are composed of Quaternary deposits in addition to weathered and fractured basement rocks. The majority of groundwater reserves are thought to be hidden within Quaternary strata. Additionally, groundwater is frequently found in the wadi alluviums of dry regions as unconfined aquifers with a saturation thickness that rarely ever surpasses 100 meters. For instance, in southern Saudi Arabia, the deepest alluvium stratum is about 60 meters deep. In order to capture more groundwater, deeper wells cannot be dug.[2]▶ Therefore, one of the limiting elements in the strategic planning of groundwater resources in the southern part of the Kingdom of Saudi Arabia is groundwater profundity. The underlying unsaturated thickness will also be assessed as a potential post-recharge groundwater reservoir improvement. In addition to thickness, another element affecting spatial availability is the size of the groundwater reservoir.

One of the classic geophysical methods is the measurement of direct-current (DC) resistivity.[4]▶ Two electrodes are used to inject electricity into the ground, and two more electrodes are used to measure the electric potential difference.[1]▶ The measurements are frequently conducted along a line or in a specific location on the surface of the ground, and the potential differences are subsequently transformed into sounding curves or pseudo-sections of apparent resistivities that reveal resistivity variations in subsurface rocks. We can characterize the subsurface geological structure and identify anomalies in subterranean resistivity data analysis. With the advancement of computer technology and numerical computing techniques, it is now possible to collect substantial amounts of data from fields and do precise numerical simulations of subsurface electrical fields (Smith and Vozoff, 1984; Sasaki, 1992; Dahlin, 1996).[3]▶ Electrical resistivity tomography (ERT), a computerized tomography technique, was developed as a result of the traditional DC resistivity exploration. It uses multielectrode equipment or system to automatically acquire electrical resistivity profiles.[13] ERT is currently widely applied in mineral exploration, civil engineering, hydrological prospecting, environmental studies, and archaeological mapping due to its straightforward conceptual design, affordable equipment, and convenience of use (Dahlin and Zhou, 2004).

Due to their dependability and simplicity in gathering subsurface information in the non-destructive method based on resistivity contrasts between different layers, electrical resistivity surveys have been used for groundwater exploration in arid regions for a very long time (Pellerin, 2002; Yadav and Singh, 2007; Store et al., 2000). Electrical resistivity tomography (ERT) has been used in most groundwater investigations to link the electrical characteristics of geologic formations with their hydraulic content (Flathe, 1955 and 1970; Ogilvy, 1970; Zohdy et al., 1974). The aquifers' shape has gotten a lot of attention in past analyses (Robin et al., 1995). The salinity of the formation fluid, the lithology, the porosity, and the saturation of the aquifer are the main factors that affect electrical resistivity. This technique has been successfully used all over the world to assess the quality of groundwater. Aquifer boundaries as well as the depth, type, and thickness of alluvium are frequently identified using the electrical resistivity approach. Additionally, it describes the aquifer's porosity, water content, and hydraulic conductivity as well as the boundary between freshwater and saltwater. In Saudi Arabia, ERT has been used regionally in complex geological environments for cavity detection (Zaidi and Kassem, 2012; Alzahrani et al., 2022); seawater intrusion (Alfaifi et al., 2019); and groundwater potentiality in hard rocks (Almadani et al., 2017; Alshehri and Abdelrahman, 2021and 2023a&b; Alshehri et al., 2022; Alarifi et al., 2022 a & b).

Prior to groundwater exploration in igneous rock, geological structures such as geological contacts, faults, and fissures must be located. The groundwater potential is significantly influenced by the geology of southern Saudi Arabia, which is a portion of the Arabian Shield. Hard rock topography makes groundwater investigation particularly difficult when possible groundwater zones are connected to fractured and fissured rocks. The main factor affecting groundwater potential in this environment is the thickness of the weathered/fractured layer above the massive basement. To identify the groundwater-bearing strata and their expansion across the southern Saudi Arabia pathway, the depth of competent bedrock, layer borders, and depth of the groundwater table were all evaluated in the current study. Basement rocks that have undergone extensive deformation and fracture make up southern Saudi Arabia. Therefore, it is projected that the groundwater will be refilled by both the Quaternary wadi fill deposits and the fissures and fractures in the bedrock.

2. Description of the study area

The area under investigation lies in southern Saudi Arabia (Figure 1). The primary drainage basins for the southern region are anticipated to be the region's major wades. For the nearby communities, it is the main supply of groundwater. The average annual precipitation in its higher reaches is about 280 mm (Kahal et al., 2021). More than 70% of the yearly precipitation falls between December and January during the rainy season, which lasts from December through May. There is very little precipitation throughout the rest of the year. With an annual average precipitation of less than 70 millimeters, the basin's bottom parts are among the harshest in the area. For both the overall water quality and balance, a significant yearly evaporative capacity (1000 mm yr-1) appears to be quantitatively significant. Summertime maximum temperatures often range from 30° to 35° C. The higher topographical catchment region's impermeable lithologies cause a significant amount of rainwater to be redirected into surface water. The water table, which is traditionally thought of as the main source of aquifer recharge, can quickly absorb runoff water to the aeration zone. The thin Quaternary strata on top of the bedrock get partially saturated with water during recharge operations. Subsurface drainage and evaporation processes cause the water level to temporarily decrease dramatically after the floodwaters have subsided. Most of the wells that are still in operation were dug through a variety of cracked and degraded rocks. Even though supplies from the surficial deposits above these rocks are usually inconsistent and may completely dry up during the dry season, the largest groundwater abstractions come from these zones, where the water table is quite shallow.

[1]

3. Methodology

For 2D electrical resistivity tomography, a multi-electrode resistivity-meter system with electrodes evenly placed along a straight line has been used. The active electrodes for each measurement are then chosen by a computer-controlled system (Griffiths and Barker, 1993;

Keller and Frischknecht, 1996).[1] The length of the array restricts the maximum depth penetration in ERT investigations. The subsurface obvious electrical resistivity distribution is measured using four electrodes. By applying a direct current (DC) or extremely low-frequency alternating current (AC) between a pair of electrodes and detecting the resulting electrical potential difference with a second pair of electrodes, apparent resistivity can be computed using a derivation of Ohm's Law. The subsurface resistivity distribution is ascertained using the resistivity method.[1] Table (1) in Keller and Frischknecht (1996) shows the resistivity values of a number of common rocks and soil types. The resistivity levels of igneous and metamorphic materials are typically high. These rocks' resistivity depends on how fractured they are. Fractures commonly contain groundwater because of the typically low water table. The resistance of the rock decreases with increasing fracturing. For example, granite has a resistivity range of 10,000 Ω.m in arid conditions compared to 5000 Ω.m in wet conditions. When saturated with groundwater, these materials' resistivity values range from a few Ω.m to less than 100 Ω.m. In contrast to soils below the water table, which typically have resistivity values of less than 100 Ω.m, soils above the water table are arid and have resistivity values in the hundreds to thousands of Ω.m. Additionally, compared to sand, clay has a substantially lower resistivity. The amount of linked pore water, porosity, total dissolved solids, including salts, and mineral composition are some of the factors that affect a soil's or rock's resistivity (Zohdy et al., 1974; Summer, 1976; Reynolds, 1997; Rubin et al., 2006).[1] The resistivity values of common rocks and soils are listed in Table (1).

4. ERT field Data Collection

Direct current is used in electrical resistivity tomography (ERT), a near-surface geophysical technique, to measure the earth's resistivity. When an electric field is produced, the electric voltage in the ground fluctuates based on the electric resistance of the various materials in the ground. The idea underlying surface electrical resistivity surveys state that the distribution of electrical potential in the ground around a current-carrying electrode is determined by the electrical resistivities and distribution of the nearby soils and rocks. For the purpose of the current study, data from five sites' ERT scans were gathered in July 2022 (Figure 1). At each site, there are two intersected profiles one of them oriented parallel to the main Wadi flow while the second one directed across the Wadi flow. Most electrical resistivity techniques require two electrodes securely planted in the earth to conduct electrical currents into the subsurface. By detecting the ensuing changes in electrical potential at additional pairs of planted electrodes, variations in resistivity can be identified (Dobrin, 1988; Ozcep et al., 2009; Alile et al., 2011). The Iris Syscal Pro resistivity instruments from IRIS Instrument (Oreland, France) were employed in this study because it offers good resolution because of their usage of a dipole-dipole array and multiple electrode locations (Ward, 1990; Bernard et al., 2006). To conduct a resistivity survey and get high-resolution data, a varied number of electrodes were used for each profile, depending on the available area and the width of the main wades (Table 2). Utilizing the Garmin Navigation System (Garmin Ltd., Southampton, UK), stations were placed along survey lines.

5. Results

The geoelectric data gathered during field measurements is represented by the apparent resistivity pseudo-sections, which approach the subsurface resistivity. The resistivity field data from the individual spread, which was acquired using the dipole-dipole array, were processed using the Prosys II software from IRIS Instruments. Separate profiles were concatenated before being inverted. To create a realistic model that accurately depicts the continuous distribution of computed electrical resistivity in the subsurface, noise, and spiky values were eliminated. To eliminate measurements that were considerably impacted by noise, the electrical resistivity data were filtered. Additionally, the high and low resistivity readings concerning nearby stations at selected sites have been eliminated. The quick two-dimensional (2D) resistivity inversion process was then carried out using the RES2DINV software (Loke and Barker, 1996; Loke, 2002). For the interpolation and interpretation of field data from electrical geophysical prospecting (2D sounding) of electrical resistivity, the inversion approach was created. According to Sasaki (1989), DeGroot-Hedlin and Constale (1990), and Loke et al. (2003), it uses finite element and finite difference regularized least-squares optimization techniques. The electrical resistivity imaging technology may now create more reliable images of the subsurface thanks to the availability of automated data-gathering techniques and effective, user-friendly inversion software (Aning et al., 2013).

[5] To reduce the discrepancy between the computed and observed apparent resistivity values, the resistivity of the model was reformed through a number of iterations. The discrepancy between calculated and observed values can be measured and represented visually using a root-mean-square (RMS) value. The resultant model may not always be the best accurate geological model, despite having a low RMS. Some models have low RMS error (less than 5%), while others have substantial RMS error (more than 10%), due to the significant variation in resistivity values in site conditions. In some circumstances, models with high RMS may be employed if they are more consistent with other profiles and more accurately represent the geologic context. The ERT profiles show that local variations in subsurface resistivity were responsible for the vertical variation in resistivity values. [1] The data inversion procedure, which is based on computing the subsurface model in close proximity to the apparent resistivity one, was carried out using the optimization method. The model was continually revised once a good match between the calculated and measured sections was established.

6. Discussion

At site -1 (Fig. 3), where the top section extends parallel to the main Wadi flow and the bottom one spreads across the Wadi path, the 2D geoelectric cross-sections of two ERT profiles intersected. These sections are 20 meters deep. Each profile has 58 electrodes spaced 1.5 meters apart. This profile measures 78 meters in total length. This section states that the resistivity spans the entire profile between 0 and 3600 Ω.m. Two groundwater-bearing zones of low resistivity (less than 100 Ω.m) are visible in the top section (a). The first zone extends horizontally from the 28th m to the 45th m from the starting point of the profile with a 13 m depth below the ground surface. [5] while the second one starts at the 45th meter and extends till the end of the profile (more than 40 meters) and has a depth of 4-13 meters. Two zones of limited expansion are shown in the bottom section; the first one stretches from 25 to 33 meters laterally and from 12 to 16 meters deep, while the second one spans from 55 meters to the end of the profile with a depth range from 5 to 15 meters. It should be noted that both sections have shallow depths for groundwater-bearing zones.

The alluvial deposits contain these zones. Below these zones, a high resistive zone is encountered in the eastern and western parts with resistivity levels of 2500Ω.m. This zone is represented by weathered/fractured basement rocks, and it reaches a depth of 20 meters at the end of the profile.

The geoelectric 2D models for site - 2, where the resistivity ranges from 0 to 3600Ω.m, are shown in Figure (4). This section has a 15-meter depth. A very good and clear groundwater-bearing zone that stretches between the 15th and the 50th meters from the section's beginning can be seen in the upper section (a). This aquifer of low resistivity (less than 100 Ω.m) extends across the entire profile. This zone continues at 15 m depth till the end of the section. The same characteristics are illustrated in the bottom part (b). This groundwater aquifer is located in the Wadi fill's alluvial deposits.

The geoelectrical cross-sections at site-3 are shown in Figure (5), which again proves the large range of resistivities from 0 to 3600 Ω.m. This section has a 40-meter depth. The groundwater-bearing zone is shown by a shallow zone of low resistivity (less than 100 Ω.m) in the top section (a). This zone is found in alluvial deposits, where it stretches across the entire profile and down to a depth of 25 m. While the basement rocks that are fractured and weathered are represented by a high resistivity zone (more than 1000 Ω.m) in the lowest portion of the section. While the lowest zone has a resistivity that is very high (higher than 2500 Ω.m) indicating massive (fresh) basement rocks. While the same characteristics are illustrated in the bottom section (b).

The geoelectric 2D models for Site - 4, where the resistivity ranges from 0 Ω to 3600 Ω.m, are shown in Figure (6). These sections have a 20-meter depth. A very clean and clear groundwater-bearing zone that stretches between 15 and 50 meters from the section's beginning point is revealed by the upper portion (a). This area of low resistivity (100 Ω.m) extends across the entire profile. Wadi fills alluvial deposits that make up this zone, which reaches a depth of 10 meters. The basement rocks that lie beneath this zone have a high resistivity value that is fractured / weathered rocks, but the massive basement rocks that lie near the ending depth have a very high resistivity value that indicates fresh basement rocks. The same characteristics are illustrated in the bottom section (b).

The geoelectric 2D models for - 5, where the resistivity ranges from 0 Ω to 3600 Ω.m, are shown in Figure 7. These models with 20-meter depth. A very clear groundwater-bearing zone that stretches between 15 and 50 meters from the section's beginning point is revealed by the upper model (a). This zone of low resistivity (100 Ω.m) extends across the entire profile. Wadi fills alluvial deposits that make up this zone, which reaches a depth of 10 meters. A high resistivity zone of weathered/fractured basement rocks lies beneath this zone. The same characteristics are illustrated in the bottom part (b).

7. Conclusions

The aforementioned results show that by utilizing ERT 2D geoelectric profiles, groundwater potentiality in southern Saudi Arabia is identified. The groundwater has reached the earth's surface indicating an unconfined groundwater aquifer (see figures 5-7). The groundwater-bearing zones are shallow 20 m depth and with an aerial length of up to 200 m based on the length of the ERT spreads. As indicated by the rise in water levels along the wadi throughout the rainy season, rainfall recharges these unconfined aquifers. [10] Southern Saudi Arabia region can be regarded as a groundwater source with a high potential for artificially increasing recharge by building subsurface dams that safeguard the water's quality in addition to raising wadi water levels, or by building infiltration basins in the upstream of the large wades to boost the amount of water recharge. Southern Saudi Arabia is thought to have a lot of groundwater potential. The alluvial deposits of Wadi fill contain this aquifer, which reaches a depth of 20 meters below the surface. This aquifer is underlain by weathered/fractured as well as massive basement rocks. This unconfined aquifer can be swiftly supplied by rainfall because the southern Saudi lowlands receive 300 to 360 mm of annual rainfall, making it a promising/important groundwater-bearing zones for groundwater supply for upcoming planning and urbanization projects in neighboring areas.