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An integrated approach for the identification of potential shallow groundwater zones in west-central Saudi Arabia

Abstract

This study aimed to identify groundwater resources at Harrat Khaybar to meet the increasing demand for groundwater for drinking and other purposes, including agricultural and industrial activities. Aquifers were assigned based on integrated electrical resistivity tomography (ERT) and hydrogeological data. Twenty-three ERT profiles ranging 590-890 m long distributed across Harrat Khaybar were acquired. The ERT data were processed to obtain 2D subsurface geoelectrical sections that indicated a variable depth for groundwater as 6-280 m. To investigate water quality, 69 groundwater samples were collected from intensively pumped wells distributed throughout the harrat. The depth to groundwater measured in these wells ranged 1.5-80 m.[0] It was concluded that Harrat Khaybar is composed of basaltic lava flows underlain by alluvial deposits, which represent two significant water-bearing formations: sub-basaltic alluvial deposits and basalt flows. The depth to the groundwater abruptly deepened from 1.5 to 80 m in the northeast and southwest directions, which could be due to groundwater-bearing formations dipping in these directions or northwest-orientated tension faults.[1] The groundwater quality was assessed in terms of total dissolved solids (TDS), which ranged from 225 to 8340 mg/l, and a TDS-drilling zone encountered in the western part of the harrat most likely resulted from groundwater mineralization.[18] The concentration of TDS generally decreased toward the east in the groundwater flow direction. The pH (6.5–8.1) of the samples indicated that the groundwater is appropriate for domestic and irrigation purposes. Test drilling should target the extensive, shallow, low resistivity zones.

Keywords: ERT, TDS, pH, water level, water quality, Harrat Khaybar, Saudi Arabia

Abbreviations

ERT	Electrical resistivity tomography
TDS	Total dissolved solids

1. Introduction

Harrat Khaybar is located in west-central Saudi Arabia north of Medina (Fig. 1). Residential communities in this harrat are spread over its entire length, and although these communities are small, they are well populated. These populations depend on groundwater for all purposes. As these populations have steadily increased, the groundwater supply from existing wells has become insufficient, so there is an urgent need to increase this supply. This study aimed to identify groundwater resources extending under the basement rocks and assess the quality of this water and its suitability for drinking and other purposes, including agricultural and industrial activities.

This study integrated geophysical data measurements, specifically electrical resistivity tomography (ERT), and groundwater hydrological data. These methods, tested globally in several areas, have proven to successfully detect and determine the quality of groundwater sources.[3] 2D multi-electrode electrical imaging systems that simultaneously consider soundings and profiling have been successfully used to map areas with fairly complex geology (Dahlin and Loke, 1998; Griffiths and Barker, 1993; Amidu and Olayinka, 2006; Olayinka and Yaramanci, 2000; Aizebeokhai et al., 2010).[0] Moreover, ERT has a wide variety of applications aimed at determining the physical parameters of rock formations and mapping geological structures for mineral and groundwater exploration and subsurface investigations (Telford and Sheriff, 1990; Lowrie, 1997; Soupios et al., 2007; Andrews et al., 2013; Rai et al., 2013; Aning et al., 2014; Arsène et al., 2018; Chen et al., 2018; Thiagarajan et al., 2018; Rizzo et al., 2019). Alshehri and Abdelrahman (2021) detected groundwater resources in Harrat Khaybar based on 11 ERT profiles at six locations (with some locations intersecting multiple resources).

2.[0] Geological setting

The geological setting of Harrat Khaybar according to Johnson (2005; Fig. 2) comprises Al Ays Group volcanic and sedimentary rocks (Kemp, 1981; Pellaton, 1981) unconformably underlain by Phanerozoic sandstones and well-bedded volcaniclastic and epiclastic sedimentary rocks.[0] The Khanzirah Complex (Fairer, 1986), represented by bodies of biotite-muscovite monzogranite and granophyre, covers the nearby area of the Khaybar (Johnson, 2005).[1] In northeastern and central-eastern Harrat Khaybar, Hamra-Badi alkali feldspar granite is partly covered by Lower Paleozoic sandstone and Cenozoic flood basalt. Older Saq sandstone, represented by flat-lying, thickly bedded, weathered pink sandstone, crops out through the basalts.[0] The Saq sandstone overlies Precambrian thickly bedded, medium-grained to conglomeratic quartzose, which is cross-bedded close to the southern end of the Harrat Khaybar. [1]Cenozoic sedimentary rocks and a Tertiary boulder conglomerate crop out on the northeastern margin of Harrat Khaybar.[1] These conglomerates comprise well-sorted and well-rounded boulders of coarse-grained pink porphyritic rhyolite with bipyramidal quartz and feldspar phenocrysts.[1] Unconsolidated Quaternary deposits mostly overlie the Precambrian basement around the harrats:[0] wadi alluvium of poorly sorted and unconsolidated sand and gravel, eolian sand as small dune fields, Sabkhah deposits formed in seasonal inland lakes, and undifferentiated gravel fan deposits and talus.

3. Hydrological setting

3.[1]1 Rainfall and climate

In the Khaybar area, rainfall, which is occasional and sporadic within the Kingdom of Saudi Arabia, is the major source of natural water for storage, and rainfall is measured by rain gauges installed throughout the harrat. The Harrat Khaybar receives 13 mm of rain per year and is classified as an arid region with high year-round temperatures. The total annual rainfall in the study area varies yearly with strong seasonal variability;[1] a high percentage of the rainfall occurs in the winter and spring (Sunbul, 2016). In the study area, rainfall dispersal varies across time and space; however, according to available meteorological data, most rainfall occurs during spring and autumn, with the least occurring during summer (Al Wagdani et al., 2016).

Hydrogeologically, Harrat Khaybar is located in the Ar Rumah basin, one of the Arabian Peninsula's biggest and longest wadis, being almost 600 km long. Heading toward the northeast, it connects with several smaller wadis. Wadi Ar Rumah was flooded after heavy rainfall from the end of 1997 to the start of 1998. During the Late Pleistocene, recurrent streamflow occurred in this wadi from October to May, reaching 32.5×10^6 m^3 (Ministry of Agriculture and Water, 1969), while there was no precipitation from June to September. The mean annual precipitation for the last ten years was 110 mm, which is very low, and it was characterized by an irregular distribution of both quantity and frequency (Sultan et al., 1998).

4. Materials and methods

Of the more than 200 groundwater wells drilled throughout the harrat, 69 widely distributed wells were selected for this study (Fig. 1). Groundwater was sampled from all 69 wells, and the depth to the groundwater was measured.[1] Most of the groundwater samples were collected from intensively pumped wells to avoid any local contamination or change in chemistry caused by evaporation or gas exchange in the wells. The water samples were analyzed in a laboratory for total dissolved solids (TDS) and pH (Figs. 3 and 4).

Electrical resistivity profiles were carried out at 20 accessible locations at Harrat Khaybar (Fig. 1). Electrical resistivity data were collected using a resistivity imaging system (SYSCAL Pro 96-channel; IRIS Instruments) with an electrode spacing of 10 m, giving a maximum length for each profile of 950 m. Reciprocal Wenner-Schlumberger arrays were used.[3] Due to the length of the array and the requirement for good contact between the electrodes and the ground, the surveys could only be carried out in large areas covered by alluvium. Hence, the spacing of the electrical sites was somewhat irregular, but a reasonably good transect over the full width of the harrat was achieved.[2] The ERT data were processed using a full version of the RES2DINV software to obtain 2D subsurface geoelectrical sections.

5. Results

5.1 Groundwater level and quality

The depth to groundwater, which ranged from 1.5 to 80 m below the ground surface, was contoured (Fig. 5). Greater depths were recorded in the northeastern and southeastern areas of the harrat. TDS includes inorganic salts and small amounts of organic matter dissolved in water. Substantial hardness, taste, mineral deposition, and corrosion are typical attributes of highly mineralized water (Basavarajappa and Manjunatha, 2015). In general, health side effects connected with the consumption of elevated TDS in drinking water are not readily obtainable, and no health-based guideline value has been suggested. Nevertheless, a guideline value of 480 mg/L based on taste factors has been established (Davis, 1966; Table 1). In the harrat, the TDS values ranged from 225 to 8340 mg/L, with a TDS-loading zone observed in the western part of the harrat. The TDS generally decreased in the groundwater flow direction toward the northeast.

Table 1: Classification of groundwater based on total dissolved solids (TDS; Davis, 1966)

TDS (mg/L)	Purpose
500	Drinking
500–1000	Permissible for drinking
1000	Suitable for agriculture
10,000	Unsuitable

In the TDS-loading zone, the acidic and alkaline properties of water can be used to evaluate its interaction with rock and other materials (Hem, 1985). The permissible pH range for drinking water, as prescribed by global standards, is 6.5–8.5 (WHO, 2004).[9] The pH of the study area samples ranged from 6.5 to 8.1, indicating that it is appropriate for domestic and irrigation purposes.

5.2. ERT data analysis

Along the entire length of geoelectric section 1 (Fig. 6a), about 30–40 m of high resistivity material overlaid low resistivity material extending ~200 m below the surface. The low resistivity section, probably a saturated zone possibly composed of gravel, extended across almost the entire width of the observed profile, but lateral variations suggested that the porosity or degree of saturation varied considerably within the zone. Low resistivity values (1-ohm m) indicated that the salinity was possibly high in some places; however, high resistivity (up to ~10-

ohm m) can be consistent with relatively fresh water. Even if water quality is similar across an entire section, observed resistivity changes can be due to variations in porosity and saturation resulting from changes within the aquifer's gravels or sediments.

Section 2 (Fig. 6b) indicated a thin (10 m thick) discontinuous surface veneer of high resistivity basaltic material or gravel.[7] Lower resistivity values extended across most of this profile, with a high resistivity block of Precambrian basement about 200–450 m along the profile at a depth of ˜100 m below the surface. The lowest resistivity values were reasonably continuous and extended across the entire profile to a depth of ˜50 m. However, even here, the resistivity values were high (50–100-ohm m) and may have represented a freshwater saturated zone. This is a potentially excellent aquifer in terms of both water quality and quantity.

Section 6 (Fig. 6c) revealed a relatively low resistivity, near-surface, 15 m thick alluvial layer that may have been a freshwater saturated zone. This was particularly evident from around 400 m onwards, and at about 750 m, the thickness increased to ˜40 m. Below this layer, the right half of the profile was underlain by high resistivities that may have represented volcanic lithologies. The high resistivities continued at shallow depth across the section as a 20 m thick layer. At distances of less than 480 m, most of the relatively low resistivity section at depths 30 m may have represented alluvium or unconsolidated material saturated with fresh water.

Patches of high resistivity were observed across section 7 (Fig. 7a) at depths of 80 m probably due to basalt flows. Below these, much lower resistivity values suggested that there was a thick layer of alluvium or unconsolidated material saturated with fresh water that may form a substantial aquifer worth testing. There were several localized areas near the surface that may have also been water saturated, for example, at 480 m along the section. While lavas occupied most of section 13 (Fig. 7b) down to ˜100 m, there appeared to be a zone at greater depth probably saturated with fresh water, but the thickness of this zone could not be determined. Section 15 (Fig. 7c) indicated that the surface lavas were only 20–30 m thick and probably underlain by an extensive saturated zone of quite fresh water. This zone may not be continuous or uniform across this section, but in places, it was thicker than 50 m, particularly near the center.

Section 17 (Fig. 8a) illustrated that the harrat material was continuous and extended down to 30 or 40 m. Near the center, there was a pronounced low resistivity saturated zone probably 100 m thick that did not appear to extend to either end of the section. This was possibly a basement channel or a fault zone. The surface lava, which was very thin from about 300 to 650 m along section 20 (Fig. 8b), was underlain by a 10–20 m saturated zone, with reasonably good quality water. At about 100 m deep toward the center, low resistivity indicated a good volume of fairly fresh water. The surface lavas were continuous and about 50 m thick along section 21 (Fig. 8c). These were underlain by an extensive saturated zone at least 80–100 m thick at about 60–80 m deep, where the resistivity values indicated that the water was quite fresh.

5. Discussion and conclusions

Surface lavas and underlying shallow aquifers were quite well defined in geoelectric sections 1–4, although with variable thicknesses. The aquifer in section 1 was probably salty, but the other sections indicated fresh water. In sections 5–7, the lava thicknesses were fairly variable, and the saturated zones, while not continuous, probably contained fresh water. Sections 8–14 mainly indicated lava, as was expected for points near the center of the harrat. The lavas thicknesses were very variable, but there were also localized generally discontinuous saturated zones throughout the sections that probably contained fresh water. Section 15 indicated thin lavas and a more extensive freshwater saturated zone. In contrast, section 16 indicated thick surface lavas and an underlying salty water saturated zone. In section 17, the lava was not as thick, and this was probably underlain by fresher water, possibly in an aquifer that was not continuous across the section. Sections 18–20 showed variable lavas and localized saturated zones with fairly fresh water at various depths. Section 21 showed continuous surface lava overlying a thick freshwater aquifer at ˜60 m depth. In contrast, in section 22, the lavas were thin and broken, with discontinuous saturated zones of fresh water. Section 23 mainly showed the effects of the surface lavas and Precambrian basement, although there were indications of a deep aquifer.

These interpretations need to be confirmed by drilling.[15]▸ It should be noted that the inversions were smoothed as part of the inversion process, so while it is not always possible to precisely define resistivity boundaries, the main features noted here are probably realistic. Test drilling should target the extensive, shallow, low resistivity zones shown in the sections: sections 1 to 4, 6 (near-surface), 14 (near-surface), and 15 would be a good start. Other sections with deeper aquifers that could be investigated include 7, 13, and 16–21.

The hydrogeological data indicated that the depth to the groundwater table deepened from 1.5 to 80 m toward the northeast and southwest. This abrupt change could have been due to northeast and southeast dipping groundwater-bearing formations or northwest-orientated tension faults.[5]▸ The groundwater TDS values ranged from 225 to 8340 mg/l, and a TDS-loading zone was encountered in the western part of the harrat, most likely the result of groundwater mineralization.[13]▸ The TDS values generally decreased toward the northeastern part of the study area in the direction of the groundwater flow. The pH varied between 6.5 and 8.1, indicating that the groundwater is appropriate for domestic and irrigation purposes.

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