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HYDROGEOLOGICAL INVESTIGATIONS IN BASEMENT TERRAINS USING GEOLOGICAL, GEOMORPHOLOGICAL AND GEOPHYSICAL METHODS, WESTERN HAMISSANA AREA, NE SUDAN

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Abstract: This study aims at identifying target zones for groundwater exploration in basement terrains using geological, geomorphological, and geoelectrical methods. The study area is located on the northwestern side of the Red Sea Hills in the western Hamissana area. It is part of the Arabian Nubian Shield (ANS), which dates to the Pan-African Era. The study area is covered by Precambrian basement rocks which are overlain by alluvial deposits. The climate in the region is arid. As a result, severe water shortage is experienced. The geological and geomorphological investigations were carried out to locate potential sites for groundwater prospecting. On this basis, three categories of groundwater potential zones were delineated as good, moderate, or poor. The electrical resistivity method using vertical electrical sounding (VES) technique was used to determine the vertical geological profile of the study area. The sequence was revealed to consist of four zones: a high-resistance unsaturated zone, an intermediate-resistance water-bearing formation, a low-resistance wet weathered basement, and high-resistance fresh basement rock. Catchment boundaries were delineated using digital elevation models, and potential locations for surface and subsurface dams were proposed to improve the groundwater recharge.

Keywords: *Groundwater exploration, Basement terrain***,** *Geomorphology, Electrical method, VES, Hamissana, Red Sea hills, Catchments*

1. INTRODUCTION

Earlier, crystalline rocks – like other hard rocks – were not given due attention for groundwater development on account of their low permeability and difficulties in water-well drilling. However, in the last few decades, due to the need for safe drinking water for vast rural populations, especially in the developing countries, crystalline rocks are being investigated in detail for groundwater development [1–3]. Groundwater is scarce in hard rock terrains; it is essentially limited to fractured and weathered zones [4]. Groundwater investigation in basement terrains involves a comprehensive study of the geology and geomorphology of the investigated area, which are influenced directly or indirectly by weathering grade, drainage pattern, landforms, and climate [5, 6].

The general geology and topography of the study area caused the observed water scarcity. The predominant rock type in the area is basement rocks. Surface topography has a significant impact on groundwater occurrences, since steep slopes increase flow and hence reduce potential recharging. Due to the scarcity of direct precipitation as a source of groundwater recharge, the natural hydrogeological conditions must be enhanced through artificial recharge [7].

The study area is situated on the northwest side of the Red Sea Hills in the Hamissana area, Red Sea State. The area is confined between latitudes (20. ° 00624-21°.0024°) N and longitudes (34. °4969°-35°.31254°) E. Hamissana area is defined by its arid environment and undulating topography landscape *(Figure 2)* which receives an average yearly rainfall of 20 to 25 millimeters *(Figure 1)*. The drainage pattern of the Red Sea Hills is fundamentally controlled by faults and folds that form rectangular drainage patterns. The main objective of this study is to use combined hydrogeological and electrical resistivity methods to detect the lithological and geological structures that control the water-bearing formations and furthermore comment on suitable methods for water resources management and development.

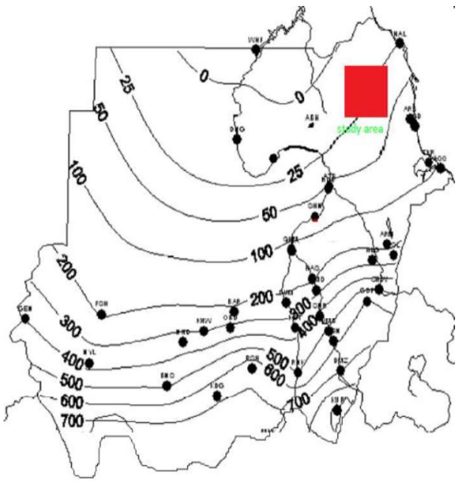


Figure 1
Average annual rainfall in the Sudan, 1971–2000, the study area shown in red box

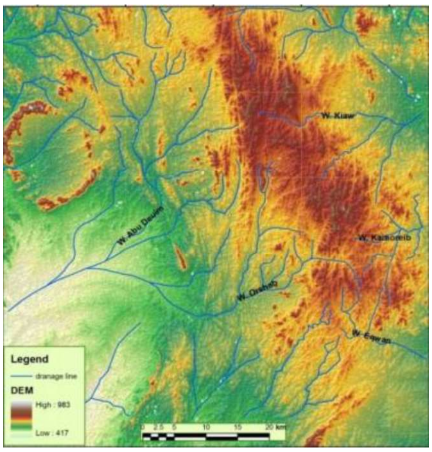


Figure 2
Digital Elevation Model of the study area

2. Geological Setting

The study area lies geologically in Red Sea hills and structurally within the Hamissana shear zone. The Red Sea Hills region of NE Sudan is part of the Arabian-Nubian Shield of Proterozoic era. It lies in the central part of the Nubian segment. It extends northwards through the eastern desert of Egypt and southwards across the Sudan-Eritrean border into the Ethiopian plateau. To the east it is bound by the Red Sea coastal plain and by the Nubian Desert to the west. Several geologists have described the geology of the Red Sea Hills of NE Sudan [8–10]. The general regional geology of the Red Sea hills can be divided into six major groups from younger to older: recent deposits, Quaternary sediments, Tertiary volcanic, Cenozoic sediments, Paleozoic sediments, and basement complex. The Hamissana shear zone (HSZ) is a massive deformation zone running north to south and is one of the greatest basement formations in NE Africa [11]. The region is dominated by metasedimentary, metavolcanic, and ophiolitic rocks, *(Figure 3)* which define an ancient boundary between the Gabeit and Gabgaba terrains [12].

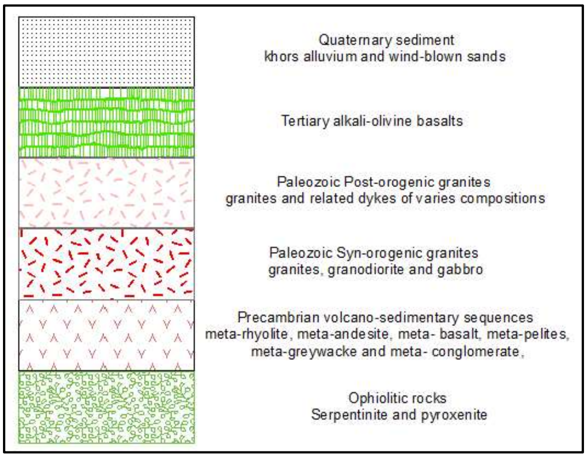


Figure 3
Geological column of study area

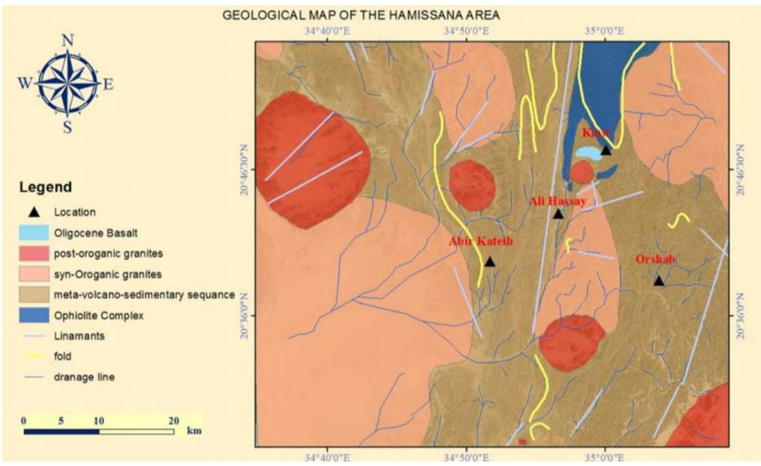


Figure 4
Geological map of the study area

These sequences are intruded by the syn- to late-orogenic and post-organic igneous intrusions. It represents important part of geology of the Red Sea Hills and comprises a very different type of rocks which are highly deformed *(Figure 3)*. The area under consideration is highly fractured with lineament concentration in the northern and southeastern parts. An earlier study [13] applied structural analysis in the study area to classify the lineament features from a hydrogeological point of view; the authors noted that the open potential fractures are commonly found in NW-SE and in NE-SW directions, while the closed shear fractures are oriented in N-S direction.

3. METHODOLOGY

The methods of the study were planned to achieve the objectives of the study. It began with the collection of available data such as meteorological, hydrogeological, and geophysical data. The hydrogeological investigation mainly focused on the study of the geological and geomorphological features that control the groundwater occurrence in the study area. Surface mapping of various lithological units, as well as their structural characteristics is part of geological studies, using satellite images as base maps. Geomorphological investigations include delineation and mapping of various landforms that make up the area and characterize the drainage systems running across the study area. The geophysical method used in this study is the electrical resistivity method using a vertical electrical sounding technique for the delineation of sub-surface layers. The vertical electrical sounding (VES) measurements were established using a Schlumberger array to acquire information about the vertical lithological variations and aquifer depths. The measurements were conducted using a portable (ABEM SAS1000) instrument. The interpretation of the resistivity data was accomplished with the assistance of IP2WIN software, assuming depth equals AB/4. This software is reliable to a good extent in determining the depth of the different boundaries and gives an automatic interpretation of the apparent resistivity.

4. RESULTS AND DISCUSSION

4.1. Geological and geomorphological investigation

Geological investigations include surface mapping of different lithological units and their structural and geomorphological features using satellite images as base maps *(Figure 4)*. Field mapping guided by remote sensing images and interpretation of geophysical data have yielded information about the thickness and composition of different rock units. The majority of the studied area is covered by a thick layer of weathered materials, which makes it a significant hydrological unit and potential ground water zone. Hydrogeologically, different rock types in the study area are grouped into three major categories *(Table 1)*:

Crystalline rocks: These include granite, granodiorite and gabbro, and the groundwater occurrence in these rocks is mainly associated with weathered horizon and fractured media. These granitic rocks are considered to be good for groundwater prospecting.

Meta volcano-sedimentary rocks: These rocks are the dominant rocks in the study area, the groundwater occurrence in these rocks is generally dependent on the degree of fracturing. In terms of groundwater availability, these rocks are defined as poor potentiality rocks.

Clastic rocks: These include alluvium and wind-blown deposits, and in these rocks the groundwater occurs within the intergranular pore spaces. The hydrogeological characteristics of the clastic rocks is moderate.

Table 1

Hydrogeological classification of the rocks in the study area

Rock group	Rock types	Aquifer structure	Potential
Crystalline rocks	Granite, gabbro granodiorite, etc.	Weathered horizon and fractures	Good
Meta Volcano-sedimentary	Meta-rhyolite, -dacite, -andesite, etc.	Fractures	Poor
Clastic rocks	Wadi alluvium	Intergranular pore space	Moderate

Geomorphological investigations include delineation and mapping of various landforms and drainage characteristics [14]. These features significantly contribute to locating favorable sites for groundwater recharge and development potential. Geomorphological mapping is accomplished via remote sensing data derived from satellite images. The erosional landforms of the study area comprised of structural hills, erosional valleys, buried pediments and valley fills *(Table 2)*.

Structural hills: These are described as large-scale rock structures. They occupy vast areas in the northern, eastern and southern part of the study area. They act as run-off zones and the groundwater potential is very poor.

Erosional valleys: These occur as narrow valleys between two adjacent structural hills. The bedrock in the erosional valleys is often weathered and has a thin layer of unconsolidated material. The potential for groundwater occurrence is very limited.

Buried pediments: These areas are covered with a rather thick layer of weathered material ranging in thickness from 20 to 70 meters. In the study area, these features are located practically throughout the whole length of the main drainage systems. The groundwater potential is described as moderate to good in these regions.

Valley fills: These are described as the deposition of unconsolidated materials in an erosional environment in hard rock terrains. Valley fills are the key landforms for the development of groundwater in a crystalline rock environment. This was found in the middle, western and southwestern parts of the study area. The groundwater prospect in this area is good.

Table 2
Landforms of the study area

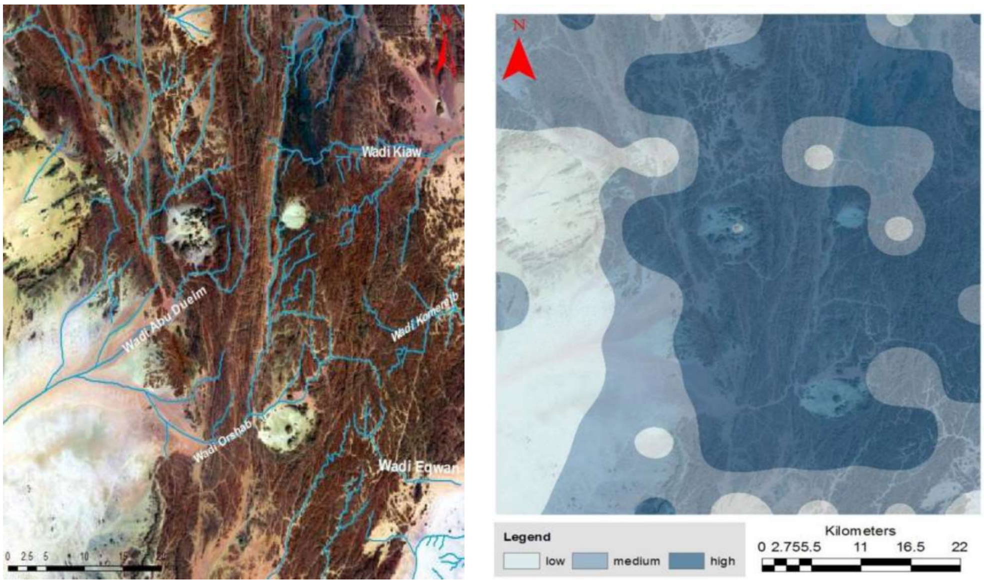
Landform	Description	Lithology	Potential
Structural hill	Large-scale rock structures	Crystalline rocks	Poor
Buried pediments	Thick layer of weathered material	Crystalline with veneer of soil cover	Moderate
Erosional valley	Narrow valley between two adjacent structural hills	Weathered rocks	Very limited
Valley fills	Deposition of unconsolidated materials in erosional environment	Coarse sediments and in situ weathered materials	Good

The drainage system is one of the critical indications of hydrogeological characteristics in basement rock terrains. The stream pattern is a reflection of the rate that precipitation infiltrates compared with the surface runoff [15]. Surface drainage is the subdued replica of topography. It is controlled by the basement rocks. The drainage pattern is mostly controlled by the underlying geological structure that causes groundwater flow to coincide with surface drainage [16]. The drainage lines were extracted and then superimposed over the Landsat image to obtain the drainage length density map. The drainage length density (Dd) is a parameter to detect the potential of groundwater storage. It is defined by the ratio of cumulative length of streams to the size of the study area *Equation (1).*

$$Dd = \sum_{i=1}^{i=n} \frac{Si}{A} \quad m^{-1} \tag{1}$$

where $\sum_{i=1}^{i=n} Si$ is the cumulative length of all streams or drainage and A is the area of the catchment (m^2).

The general slope of the area is from north to the south flanks, which represents the inconsiderable variation in elevation with the adjacent surrounding areas. In the study area, the dendritic and parallel types are the most common drainage patterns. Parallel types of drainage patterns are an indication of the presence of structures that act as conduits or barriers for groundwater systems. Generally, low drainage density is associated with areas of high resistance or permeable surface and low relief. High drainage densities are found in areas with impermeable subsurface materials and mountainous relief, which have poor infiltration rates *(Figure 5)*.



A *B*

Figure 5

(A) Drainage map and (B) drainage density map of the study area

4.2. Geophysical investigation

The use of geophysics for groundwater exploration has intensified during the last few years due to the rapid advancement in computer software and numerical solutions. Because of its simplicity, vertical electrical sounding (VES) has proven to be very popular in groundwater prospecting. The geophysical electrical resistivity method was applied to define the anomalies, thickness and lithological variation of the alluvial and basement aquifers. In this study a total number of 24 vertical electrical sounding points (VES) using Schlumberger configuration were carried out based on the geological and geomorphological investigations to identify the vertical lithological sequences *(Figure 6)*. VESs were conducted in the key micro-watersheds such as Wadi Orshab, Wadi Abu Deuim and Wadi Eqwan. The VES points are interpreted using IP2WIN software. Based on the interpreted data it was found that the resistivity of the basement complex rock ranges from high values of 6290 Ohm.m to infinity, with the higher values indicating hard basement rocks while lower values referred to weathered and cracked basement rocks. The surface deposits may be classified into two groups: dry topsoil (sands and gravels) with resistivities more than 700 Ohm.m, and wet clay and clayey sand with resistivities between 10 and 100 Ohm.m *(Figure 7)*.

Figure 6
Locations of the VES stations in the study area

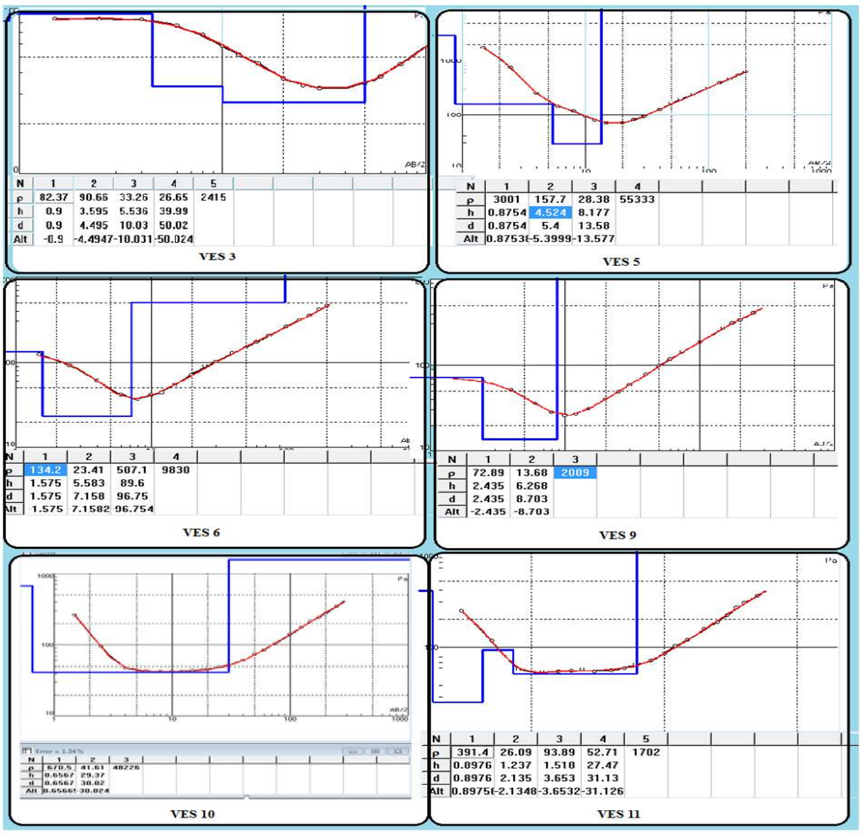


Figure 7
The VES curves in Wadi Orshab

Generally, the curves show that succession consist mainly of four layers from the surface: dry topsoil at 1–3 m, followed by alluvial deposits, and then weathered basement overlaying the fresh basement of higher resistivity values. The result of the geophysical investigations revealed that the succession consists of two aquifers: the shallow alluvial aquifers at depths ranging from 8 to 15 meters below the ground surface; and the deep weathered/fractured basement rocks aquifers that range in depth between 20 and 50 meters below the surface.

4.3. Aquifer Recharge Management

The term management of aquifer recharge (MAR) is now being increasingly used for artificial recharge to imply an additional input of water underground besides natural infiltration [17]. The improvement of the aquifer recharge is done through constructing surface and subsurface dams *(Figures 8–10)*. Surface dams are important in groundwater management scenarios as they provide natural storage for water for use during a dry period. The subsurface dams are implemented to prevent water from migrating beyond the expected catchment area toward a neighboring area. Subsurface dams are feasible in narrow and gently sloping valleys where the bedrock occurs at a shallow depth, overlain by a valley-fill deposit of 4–8 m thickness. The main aim of these dams is to increase the groundwater quantities and reduce the underground seepage, which finally leads to the enhancement of the hydrogeological condition in the area.

Watershed analysis

The annual rate of precipitation in the study area ranges between 25 and 50 mm, and the annual evapotranspiration is much greater than the annual precipitation. From the literature in similar areas in Sudan, about 85% of the precipitation during the rainy season is lost due to evaporation. Accordingly, the above-mentioned data was used in this study to calculate the total yield of each wadi *(Equations 2–4)*. The calculated watersheds are Wadi Orshab, Abu Deuim and Eqwan.

The course of Wadi Orshab runs parallel to the direction of the release fractures in NE-SW direction *(Figure 8a)*. It is one of the biggest and most important watersheds in the study area. The main rock type in Wadi Orshab is meta-volcano sedimentary intruded by synorogenic granite. The catchment area of Wadi Orshab is about 200×10^6 m^2 and the total yield of Wadi Orshab is:

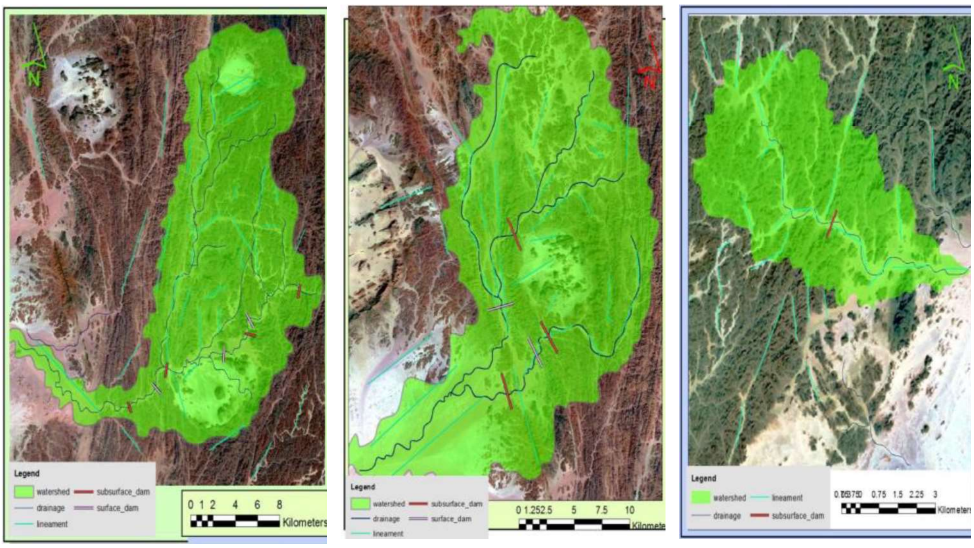
$$Q = 200 \times 10^6 \text{ m}^2 \times 4.5 \times 10^{3-} \text{ m} = 1035 \times 10^3 \text{ m}^3 \quad (2)$$

Wadi abu Deuim watershed drains the northern part of area *(Figure 8b)*. The course of Wadi Abu Deuim runs parallel to the direction of the extension and tension fractures in NW-SE direction. The main rock type of Wadi Abu Deuim is synorogenic granite. The catchment area is about 490×10^6 m^2, the annual rainfall is the lowest value in the area, therefore the value of 25 mm/y was used for calculation of the annual precipitation. The remaining water from the annual rainfall is about 3.75 mm on average; using the same remaining percent, then the total yield is:

$$Q = 490 \times 10^{6}\ m^{2} \times 3.75 \times 10^{-3} m = \tag{3}$$

Wadi Eqwan watershed is calculated at about 215 × 10^6 m^2 *(Figure 8c)*. The remaining 15% of the average annual precipitation (30 mm/y) is equal to about 4.5 mm, so the total yield of Wadi Eqwan is:

$$Q = 215 \times 10^{6}\ m^{2} \times 4.5 \times 10^{-3}\ m^{3} = 968 \times 10^{3}\ m^{3} \tag{4}$$



(a) *(b)* *(c)*

Figure 8

The watersheds of Wadi Orshab, Abu Duiem and Eqwan, including the suggested location of surface and subsurface dams

5. CONCLUSIONS

The aim of this study is to assess the groundwater resources in the Hamissan area by combining different exploration peckages including geological, geomorphological, and geophysical methods. The integration of these methods has proven to be efficient in identifying the groundwater potential zones. On the basis of the geological and geomorphological investigations, three classes of groundwater potential zones were revealed: poor, moderate and good. The electrical resistivity method using vertical electrical sounding technique was applied to detect the vertical lithological variation and the thickness of each unit. The result of the geophysical investigations revealed that the area contains two types of aquifers: shallow alluvial aquifers and the deep weathered/fractured basement rocks aquifers. Due to scarce annual precipitation, high evaporation and steep slope in the study area, several locations of surface and underground dams have been proposed to improve groundwater recharge. To improve water supply in the study area, this study recommends application of electromagnetic and ground penetration radar to acquire more information about the thickness of the saturated weathered materials. Based on the investigation and interpretation of the data during this study, we also recommend construction of rainfall stations and runoff gauges to obtain more information about water balance in the study area.

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