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RESEARCH ARTICLE

DECIPHERING GROUNDWATER POTENTIAL WITH THE UTILIZATION OF ELECTRICAL RESISTIVITY GEOPHYSICAL METHOD, SOUTHEASTERN PART OF THE RED SEA STATE, EASTERN SUDAN

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ABSTRACT

This study aims to investigate the groundwater accumulation in some rural areas in three localities of the Red Sea State, eastern Sudan. The area is composed of basement rocks overlain in some parts by recent alluvial sediments and Delta deposits. The hydrogeological investigations were confirmed by the conductance of field electrical geophysical survey in which 10 Horizontal electrical profiles and 23 Vertical Electrical Sounding measurements have been executed. The acquired data have been interpreted using IPI2win software. At the shallow basement areas of the investigated locations, the Horizontal Electrical Profile (HEP) have revealed anomalies associated with low resistivity values which is indicative for water-bearing zones. Qualitatively, the dominant types of resistivity curves are KHQ and HKHQ curve types. Quantitatively, the interpreted subsurface layering and the corresponding lithologies reflected the subsurface configuration along the sets of vertical electrical sounding stations. The dominant aquifers in the investigated locations are encountered within; the weathered/fractured zones in the Basement complex areas where the aquifourous zones are characterized by resistivity values of (22 to 180 ohm m). In Recent Alluvial/ deltaic deposits that covers huge area in Tokar locality of the Red Sea State, the aquifourous zones are characterized by resistivity values of (35 to 82 ohm m). The outcomes of the geophysical investigations have been combined with geological and hydrogeological knowledge, in order to define the most potential sites in the targeted localities of the Red Sea State.

KEYWORDS

groundwater investigation, resistivity, HEP, VES, Red Sea State, Sudan.

1. INTRODUCTION

The study aims to investigate the groundwater accumulation in some rural areas in three localities of the Red Sea State, eastern Sudan. These are Sinkat, Suakin and Tokakar localities that bounded by Latitudes 17o 30/ 00// N- 20o 00/ 00//N and longitudes 36o 00/ 00//E – 38o 00/ 00// E, (Fig. 1).

The study area represents the southeastern part of the Red Sea region of Sudan. The Sudanese Red Sea coast is extends from the Egyptian border in the north at latitude 23° 00´´ N to the Eritrean border in the south at 18° 00´´ N, and from the mountainous area at longitude 35° 00´´ E on the west to the Sea coast at 37°15´´ E. The Red Sea region is a typical arid zone, where the average annual evaporation is much greater than the annual average precipitation (200 mm/year). The Red Sea Hills represent a climatic border; hence the summer rains from July to September affected the western part of the Hills. The coastal area is affected by the winter rains mostly from November to January (Elsheikh et al., 2009). The region is dominated by a high elevated terrain of basement rocks. Therefore, the groundwater is limited and affected by the climatic, geological and topographical prevailing conditions. Thus, the recognition of new groundwater supply sources in the Red Sea State are, hydro-geologically quite complex that causes the unsuccessful of water conveniences. Accordingly, proper sitting is required where apposite subsurface layering and groundwater potential need to be explored. Hence, geological and hydrogeological assessments followed by geophysical investigation have been carried out.

The relevance of geophysical methods helped in locating zones of enhanced secondary porosity such as weathered/fractured basement rocks (Nayl et al., 2025). Application of geophysical methods is useful in the determination of types and depths of geological formations (consolidated or unconsolidated), depth of weathered/ fractured zones, depth to groundwater horizons, depth to bedrock and groundwater salinity (Bouwer, 1978). Moreover, the application of geophysical methods helping in sitting of productive water targets in various environmental settings (Ariyo and Adeyemi, 2012). The electrical resistivity method is benefits in groundwater exploration that have resistivity characteristic to identify the saturated zones from the adjacent impervious or dry layers. The resistivity method gives the possibility to identify the presence of groundwater according to rock porosity or fracturing.

The present article shows the conducted geophysical measurements and the interpretation of the results with conclusive discussion for identifying the most potential sites for groundwater occurrences in some targeted rural communities in the three targeted localities (Fig. 1). Nine locations were investigated using electrical resistivity methods. These locations belong to Tokar, Sinkat and Suakin localities. The coordinates of these

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locations are given in Table (1) and they are shown by Figure (2).

The main objective of the current investigations is to recognize possible potential targets for groundwater occurrences based on the geo-electrical survey taking into consideration the climatic, topographic and geological condition that affecting the occurrences of groundwater in areas mostly occupied by basement rocks.

Figure 1: Locations of the Targeted localities in the Red Sea State, eastern Sudan.

Table 1: Coordinates of the investigated sites in the Red Sea State.			
Locality	Site	Coordinates *(DD.DDDDDD)*	
		Longitude	Latitude
Tokar	Ashat	37.356158	18.689368
	Gabayab	37.113049	17.96004
	Krembet	37.687670	18.259981
	Farak Saleib	37.466662	17.862167
	Gedaiaf/Khor Langeib	37.280384	17.562228
Sinkat	Shakan	36.791009	18.654638
	Braseet	36.689977	18.490461
	Asout Station	36.991323	19.316325
Suakin	Tamay	37.213429	18.935572

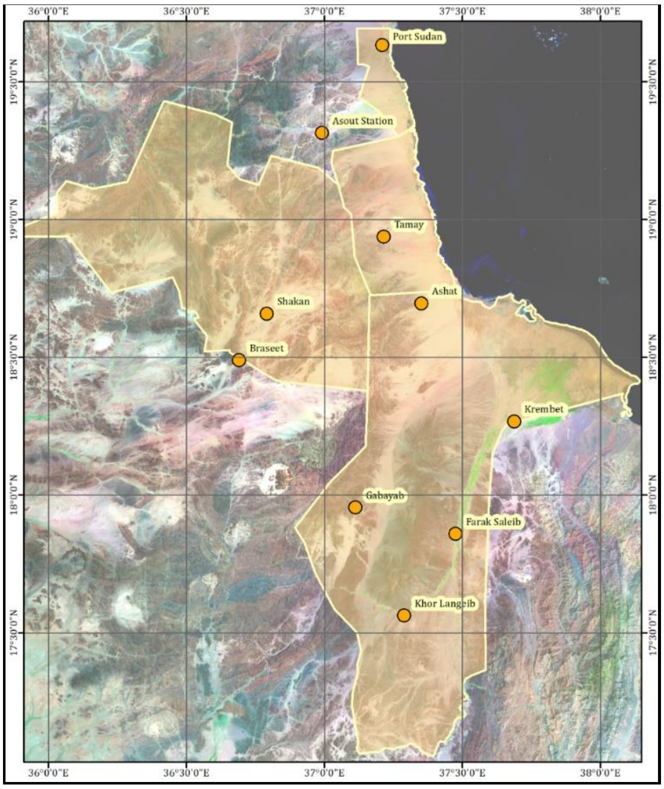

Figure 2: Location map of the investigated sites in the Red Sea State.

2. Geological Setting

Regard the geology of the Red Sea State; more than 90% of the total area of the state (210,000 Km2) is occupied or underlain by basement rocks (volcanic and crystalline rocks). The geology of the Red Sea region has been widely investigated (Ruxton,1956; El Nadi, 1984, Kroner et al., 1987; Robertson Research International, 1988; Bunter and Abdel Magid, 1989; Babikir, 1999). However, the Red Sea Hills of NE Sudan is lies in the central part of the Nubian segment of Proterozioc era. The Nubian sheild is bound by the Red Sea coastal plain to the east and by the the Nubian Desert to the west (El Nadi, 1984).

The hills is comprise a semi- desert plateau representing narrow strip of rugged terrene of more than 200 km wide and rising up to 2000 m above sea level (amsl). The major stratigraphic units in the Red Sea State (Fig. 3) includes the igneous and metamorphic rocks of the "Basement Complex" of Precambrian age. A Late Cretaceous to Cainozoic sequence of variable thickness in rift basins lies unconformably over the "Basement Complex. The outcroping Cainozoic sedimentary units includes the lower part clastic-carbonate rocks of middle Miocene, and the upper part clastic sediments of later age in the coastal zone (Bunter and Abdel Magid, 1989).

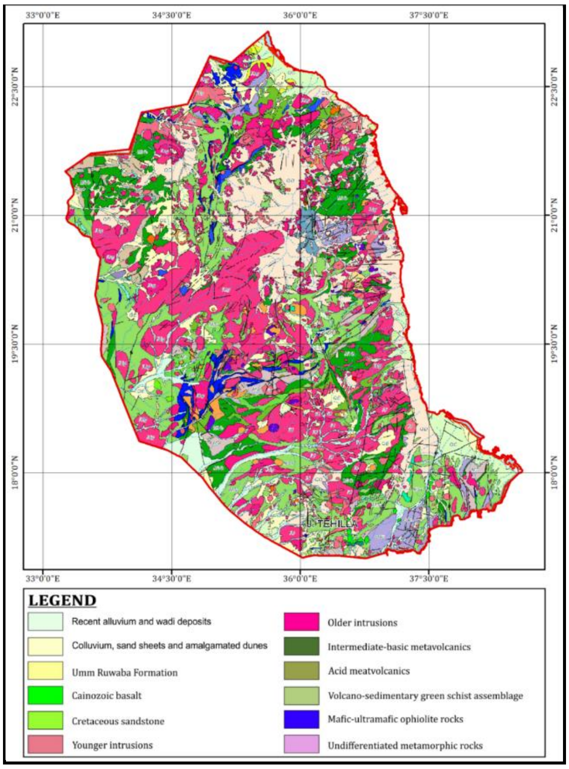

Figure 3: Regional geological map of the Red Sea State, adapted from geological map of Sudan (GRAS, 1989).

All the investigated localities in the Red Sea State are dominated by the basement complex rocks. However, large areas of Tokar locality are covered by deltaic and alluvial deposits (Fig. 4, Plate 1).

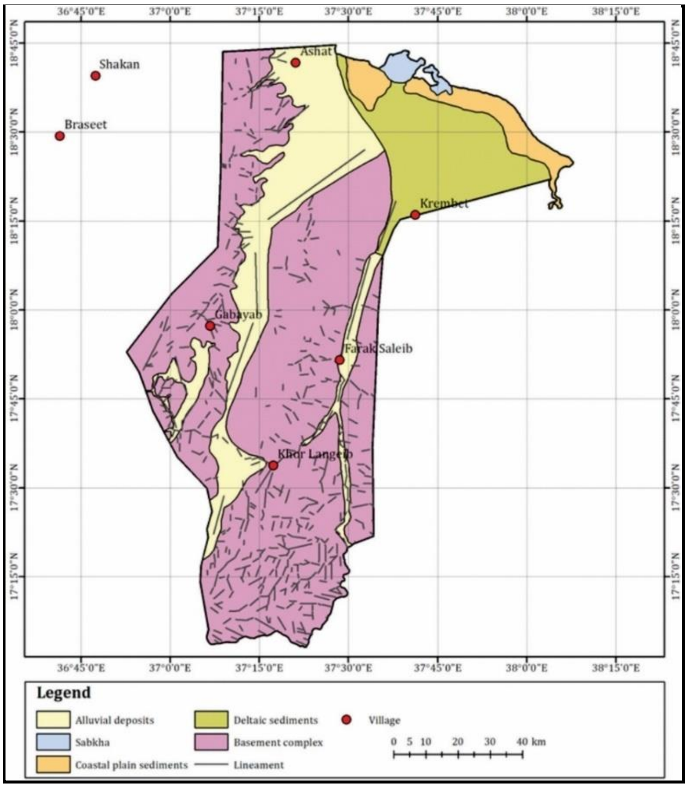

Figure 4: Surface geological map of Tokar Locality based on satellite image interpretation and field check.

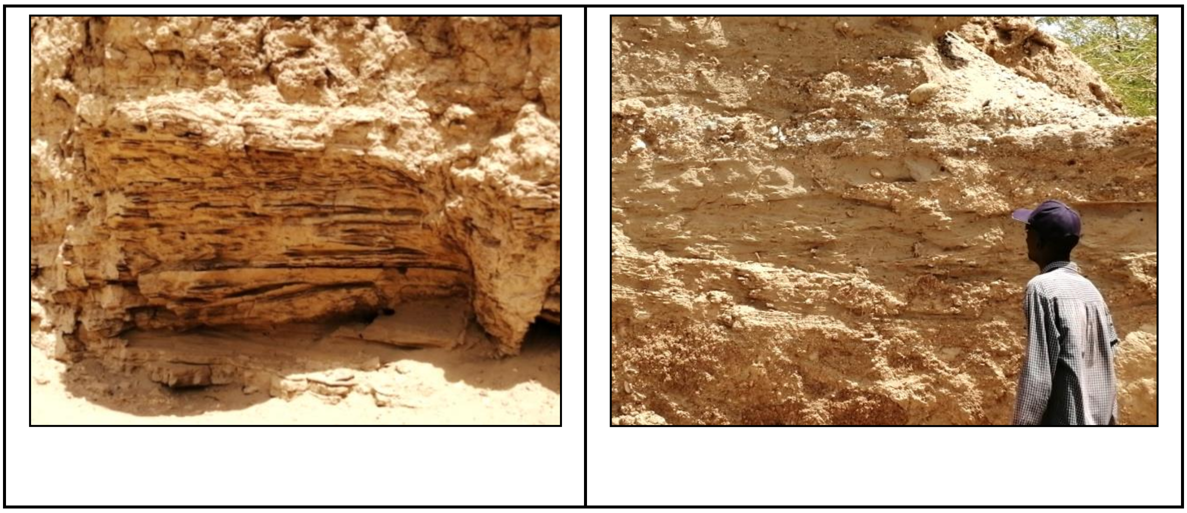

Plate 1: Recent alluvial continental deposits observed in the investigated locations: (left): Farak Salaib, (right): Gedaiaf, Tokar locality.

3. Hydrogeological Setting

The dominant basement rocks in the Red Sea State are practically nonporous and impermeable. Potential composite aquifers were developed within the weathered overburden and fractured bedrock of these crystalline rocks (Wright, 1992). Some other groundwater bearing zones are encountered in the sedimentary deposits overlying the basement rocks. Nevertheless, using three GIS layers including, simpilified geological map, fractures and existing wells, a hydrogeological map for the Red Sea State have been produced (Fig. 5). From this map, the main water-bearing formations in the Red Sea State can be outlined as follows:

3.1. Weathered-Fractured Basement Rocks

Like in so many parts of Africa where many communities in arid and semi-arid regions, rely on weathred/fractured crystalline basement rocks as the primary source of water supply. Many of the rural areas in Sinkat, Suakin and part of Tokar localities are underlain by weathered/fractured basement water-bearing systems. In these areas, basement rocks such as schist, granitoids and volcanics represent good groundwater- prospect areas where, there are intersections of fracture systems which are commonly in relation to the drainage pattern as the source of recharge. This fact helped in the orientation of geophysical measurements.

3.2. Alluvial deposits

The Quaternary alluvial, colluvial outwash of the khors and the drainage basins, where extensive wadi systems debouch on to the littoral forming a series of alluvial fans and deltas which are composed of gravels, sands, silts and clays. The khor courses are filled by unconsolidated silts, sands, gravels and boulders. Lenses of freshwater limestone (calcareous conglomerate) have been described from some khors (Whiteman, 1971; Hussein, 1975).

3.3. Coastal plain deposits

The coastal plain deposits are geologically composed of continental to shallow marine sediments of Tertiary to Quaternary age and overlie the basement rocks. These included Sabkha, fluvial and windblown deposits forming the mixed sediments of continental and marine sources along the Red Sea coast.

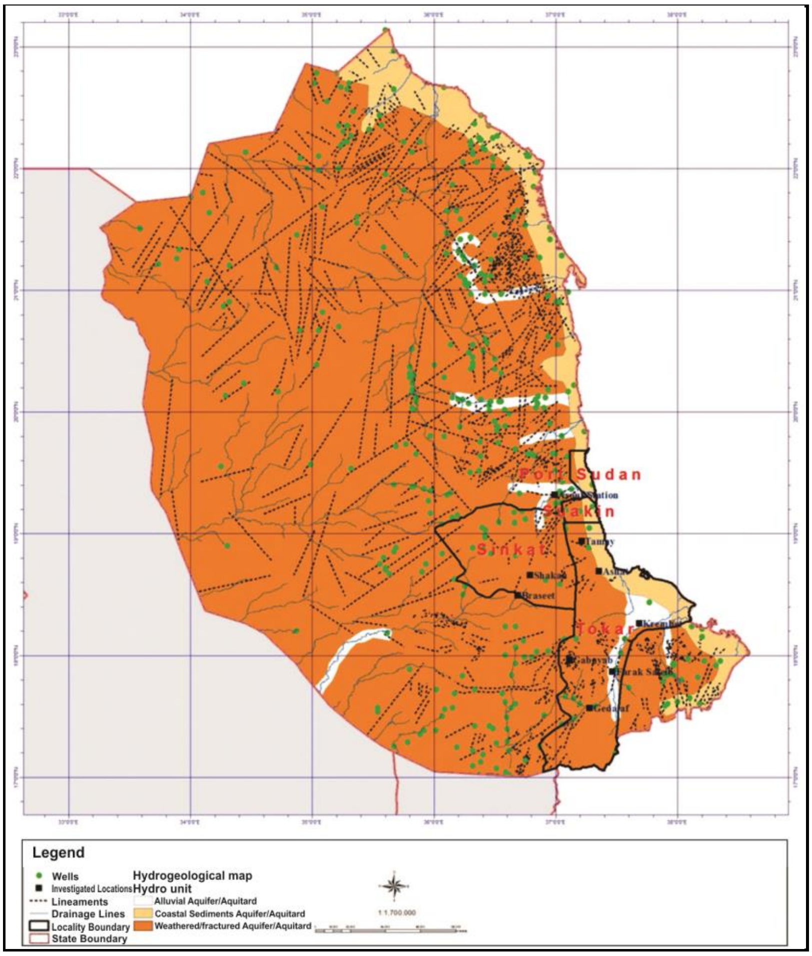

Figure 5: Hydrogeological map of the Red Sea State

4. Methods Of Investigations

Electrical resistivity methods, both quantitative and qualitative investigations methods, are based on the principle of Ohm's law: measurement can be referred back to the true resistivity of traversed formations (Bakkali and Bouyalaoui, 2005). The usual practice in the field is to apply an electrical direct current (DC) between two electrodes implanted in the ground to measure the difference of potential between two additional electrodes that do not carry current. Usually, the potential electrodes are in line between the current electrodes. The distribution of potential can be related theoretically to ground resistivity and their distribution. In this way, Electrical resistivity measurements have been conducted in the targeted localities using an ABEM SAS-1000 Terrameter (Sweden). The instrument is relatively powerful and has high sensitivity. The instrument has been used with appropriate electrodes, cables on reels, and other accessories.

Horizontal Electrical Profile (HEP) and Vertical Electrical Sounding (VES) techniques have been employed. HEP technique using Wenner array has been used for determining the horizontal/lateral variation of resistivity, in some selected sites of the targeted localities. The VES technique with Schlumberger arrangement was employed for delineating the lithology and the thickness of the subsurface strata.

A number of eight HEP were conducted utilizing Wenner array in some selected sites of the Red Sea State. The sites where HEP technique is applied are characterized by the presence of shallow basement rocks. In the Wenner array configuration the spacing between successive electrodes remains constant and all electrodes were moved for each reading. The four electrodes are collinear and the separations between adjacent electrodes are equal (a) with M, N in between A, B. The choice of electrode spacing would primarily depend on the depth of the anomalous resistivity aspects to map the targeted zones (Sharma, 1986; Parasnis, 2012). The nominated anomalies at each profile were verified by Vertical Electrical soundings using the Schlumberger configuration with a maximum half-separation AB/2= 800 m. In this technique the central point of the electrodes array remains fixed, while the spacing between the electrodes are increased to obtain more information about the deeper parts of the subsurface. 23 points of Vertical Electrical Sounding (VES) measurements (Plate 2) were conducted in the targeted locations of Tokar, Sinkat and Suakin localities of the Red Sea State.

Plate 2: Schlumberger Array for VES measurement using SAS 1000, Red Sea State

5. Results And Discussion

Detailed information about the measured eight profiles is provided in Table (2). Points in the HEP lines with anomalous low resistivity values were selected as targets for later VES measurements conduction. The measured profiles are illustrated by Figures (6-7).

Table 2: Details of the measured profiles in the Red Sea State

Locality	Site/ profile	P. Start point	P. End point	AB/2 (m)	MN/2 (m)	Constant K=2πa	Resistivity Range (Ωm)	Nominated point for VES
Tokar	Ashat	18.68661 N 37.34368 E	18.67768 N 37.35078 E	150	50	314.16	40-110	Station 36
	Gabayab	17.9545 N 37.11256 E	17.95335 N 37.10934 E	150	50	314.16	100-300	Station 14
	Brasset (P1)	18.50915 N 36.6959 E	18.50837 N 36.69162 E	150	50	314.16	50-240	Station 18
	Brasset (P2)	18.50915 N 36.6959 E	18.50837 N 36.69162 E	150	50	314.16	50-140	Station 32
Sinkat	Asout Station (P1)	19.32927 N 36.94651 E	19.3208 N 36.94728 E	150	50	314.16	40-200	Station 11
	Asout Station (P2)	18.32927 N 36.94651 E	18.3208 N 36.94728 E	150	50	314.16	50-600	Station 21
	Shakan (P1)	18.66968 N 36.79642 E	18.66694 N 36.80059 E	150	50	314.16	05-110	Station 13
	Shakan (P2)	18.6631 N 36.77569 E	18.66396 N 36.77097 E	150	50	314.16	50-240	Station 18

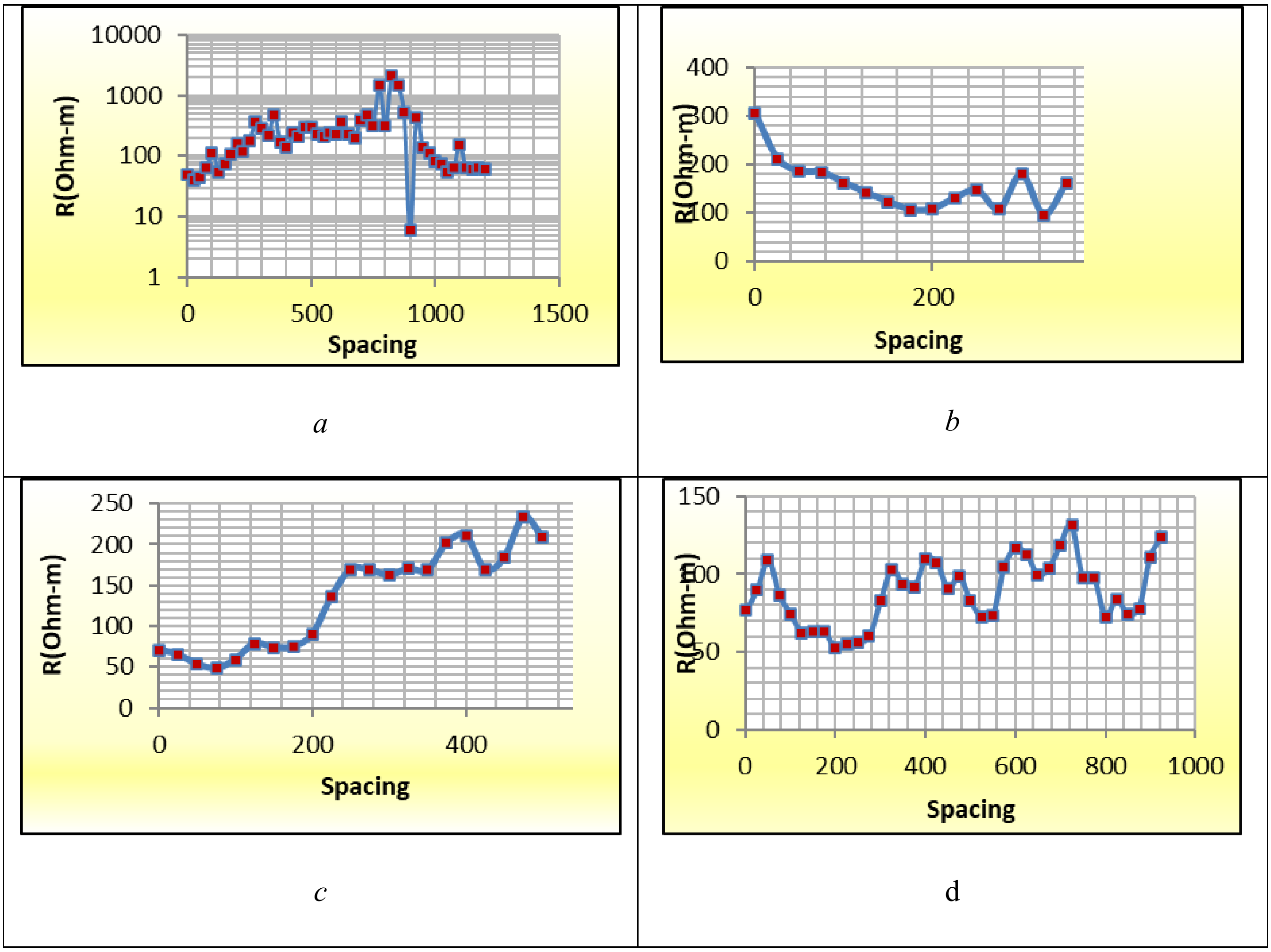

Figure 6: HEP lines conducted in Tokar Locality: *a-Ashat village, b-Gabayab village, c-P1-Braseet village, d-P2-Barasset village.*

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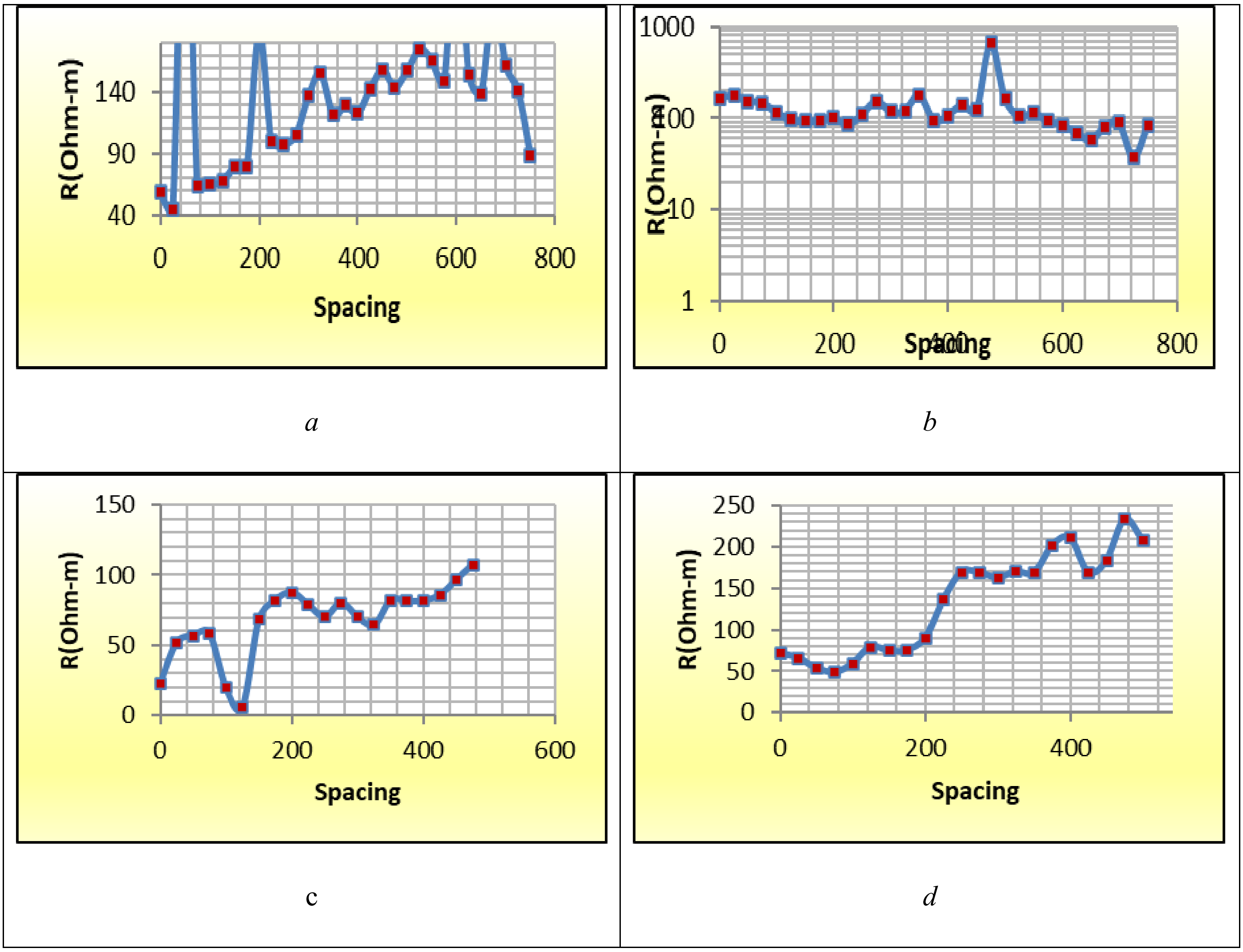
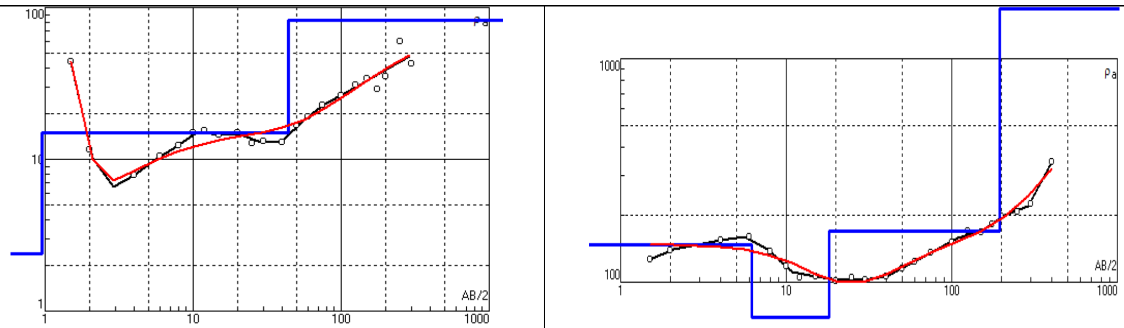


Figure 7: HEP lines conducted in Sinkat Locality: a- *P1-Asout station,* b- *P2-Asout station,* c- *P1- Shakan village & d- P2-Shakan village.*

Based on the fundamental principles and methodologies of the geophysical survey, the collected data are interpreted qualitatively and quantitatively. HEP survey data are entered into the computer and processed using Microsoft Office Excel Software to determine the lateral variations of the geologic formations. The low resistivity values are considered as conductive zones inside the basement rocks that interpreted as saturated weathered/fractures media on which the VESes locations were selected, (Figs. 6 & 7)

VES data were entered to the computer and curves were plotted using IPI2win interpretation software to determine the thickness, nature and lateral variations of the subsurface geological formations which are used to obtain a complete geological picture of the project area.

All the observed VES curves reveal relatively thick multi-layered earth. The dominant curve types are indicating four to five geo-electric layers reflecting thick and high resistivity ground. Basement and alluvial sediments trends are revealed within the Red Sea surveyed areas (Fig. 8).



N	1	2	3	4
ρ	1266	2.38	15.1	82.3
h	0.342	0.614	42.9	
d	0.342	0.956	43.8	
Alt	-0.3415	-0.9558	-43.82	

a

N	1	2	3	4
ρ	147	69.6	170	22420
h	6.2	12	177	
d	6.2	18.2	195	
Alt	-6.196	-18.16	-194.8	

b

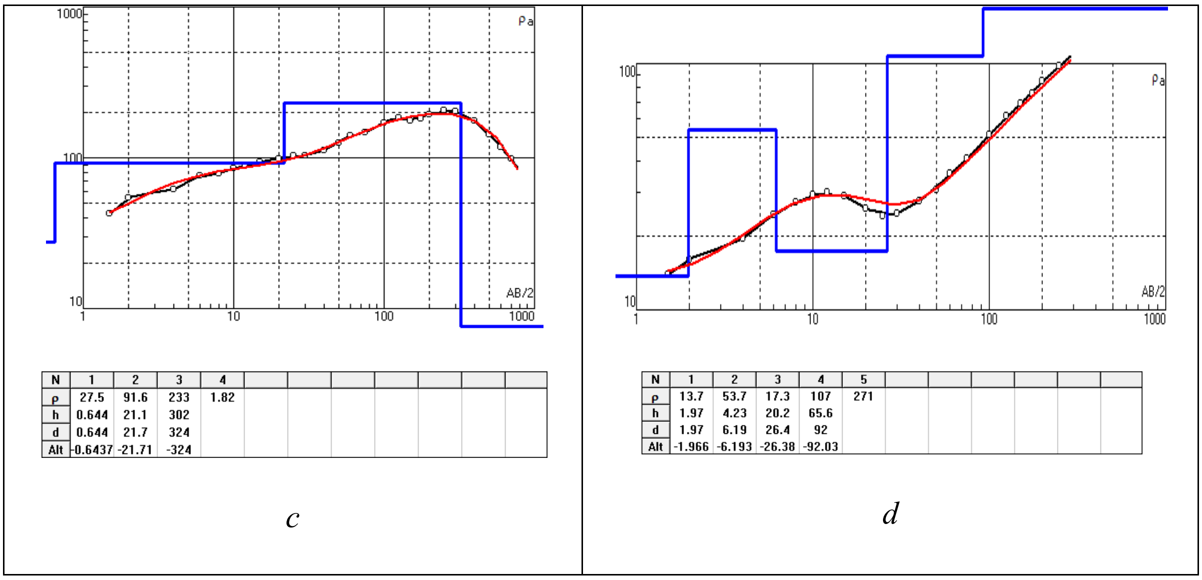


Figure 8: Typical resistivity Curve tapping crystalline basement rocks below alluvial sediments in Tokar Locality; a-Farak Saleib village, b-Gedaiaf village V1 & c-Gedaiaf village V2, and d-Shakan village in Sinkat Locality.

The interpreted Vertical Electrical Sounding (VES) data revealed the presence of various geo-electric layers and tolerable their classification into different resistivity type curves. observed that the type of apparent resistivity curve obtained by sounding over horizontally stratified medium is a function of resistivity and thickness of the constituent layers that characterize the geological medium and the employed electrode array in sounding measurements (Bhattacharya and Patra, 1968). Accordingly, from the qualitative view, the dominant curve types are shown on Table (3) below;

Table 3: Aquifers and resistivity curve types

Locality	Location	Aquifer type	Curve type	Remarks
Tokar	Ashat	Weathered/fractured basement	KHQ	Aquifer resistivity is 180Ω.m
	Gabayab	Weathered/fractured basement	KHQ	Aquifer resistivity is 116Ω.m
	Krembet	Alluvial/Deltaic deposits	HKHQ	Aquifer resistivity 35Ω.m
	Farak Saleib	Alluvial/Deltaic deposits	HKHQ	Aquifer resistivity is 82Ω.m
	Geadaiaf/ Khor Langeib	Weathered/fractured basement	AHQ	Aquifer resistivity is 40Ω.m
Sinkat	Shakan	Weathered/fractured basement	KHQ	Aquifer resistivity is 107Ω.m
	Brasset	Weathered/fractured basement	KHQ	Not confirm
	Asout Station	Weathered/fractured basement	AHQ	Aquifer resistivity is 22Ω.m
Suakin	Tamay	Weathered/fractured basement	HKHQ	Aquifer resistivity is 40Ω.m

Quantitatively, the interpreted resistivity values in terms of a variety of geological formations are based on a resistivity-depth model that produces the observed resistivity from a depth sounding (Asfahani, 2007). The apparent resistivity and layer thicknesses were converted into relative geological meaning using the knowledge of geological data and express geological visual observations. Accordingly, groundwater potential aquifers producing zones have been delineated for the investigated sites of the targeted locations in the Red Sea State. Commonly the interpreted VES results revealed a maximum of five geo-electric layers. These layers with their corresponding thichnesses interpretation are shown on Table (4) for each location.

Table 4: The results of the interpreted VES curves in the targeted locations of the Red Sea State.

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Locality	Village	VES No.	Layer 1		Layer 2		Layer 3		Layer 4		Layer 5		Layer 6	
			ρ	h	ρ	h	ρ	h	ρ	h	ρ	h	ρ	h
Tokar	Ashat	RS 1	99.5	2.3	46.4	10.8	33.4	29.6	180	156	6448	-	-	-
		RS 2												
	Gabayab	RS 3	77	2.26	26.7	21.5	1551	-	-	-	-	-	-	-
		RS 4	458	1.66	116	74.8	9496	-	-	-	-	-	-	-
		RS 5	126	3.52	17.6	13.4	191	139	16986	-	-	-	-	-
	Krembit	RS 6	3477	0.384	178	0.585	1801	1.38	483	56.4	300	390	34.6	-
		RS 7	14.5	0.364	87.7	11.7	115	68.8	25.9	462	0.78	-	-	-
		RS 8	27.5	0.644	91.6	21.1	233	302	1.82	-	-	-	-	-
	Fraksaleib	RS 9	1266	0.342	2.38	0.614	15.1	42.9	82.3	-	-	-	-	-
		RS 10	2599	2.09	246	8.05	28.3	92.8	147	-	-	-	-	-
		RS 11										-	-	-
	Shakan	RS 12	13.7	1.9	53.7	4.23	17.3	20.2	107	65.6	271	-	-	-

Sinkat		RS 13	20.3	0.832	282	0.757	12.7	22.6	1174	-	-	-	-	-
	Brasset	RS 14	59.88	7.52	9.84	8.7	213	24.6	908	-	-	-	-	-
		RS 15	843	0.441	60.4	1.94	12.4	22.5	3677	-	-	-	-	-
	Asut Station	RS 16	896	0.41	79.5	3.11	22.2	26.9	14523	-	-	-	-	-
		RS 17	181	2.89	57.4	17.7	42.7	29.2	304	-	-	-	-	-
Suakin	Gadaeif/ Khor Langeib	RS 18	327	0.499	2351	0.558	317	5.83	12.1	58.7	9354	-	-	-
		RS 19	714	0.682	107	7.26	40.3	29.9	1391	-	-	-	-	-
		RS 20	147	6.2	69.6	12.0	170	177	22420	-	-	-	-	-
	Tamay	RS 21	632	0.778	264	2.85	509	19.8	141	242	1369	-	-	-
		RS 22	17030	0.218	220	11.3	98.5	16.1	40.1	334	1152	-	-	-
		RS 23	14622	0.288	190	0.693	1195	2.43	365	22.5	425	95	220	-

From the comparison between the results of each survey interpretation given by the software and the available lithological data of the drilling logs in the targeted locations of the Red Sea State, local experimental resistivity scale can be established (Table 5).

Table 5: Interpreted apparent resistivity and the corresponding lithology, Red Sea State.

Table 5: Interpreted apparent resistivity and the corresponding lithology, Red Sea State.

Lithology	Resistivity (Ω.m)
Clay	1-20
Silt/sand	20-200
Pebbles/gravels	200-1000
Weathered basement	100-500
Fresh basement	≥500

From Table (4), it is clear that the interpreted resistivity data led to distinguish the succession of layers informing about the heterogeneity of the underground formations at each location. With reference to this table and the scale shown by Table (5), the subsurface geological successions beneath VES points in the targeted locations of the Red Sea State could be deduced (Table 6).

Table 6: Subsurface geological successions in the targeted locations of the Red Sea State delineated from the Quantitative interpretation of VES data.

Locality	Village	VES No.	Subsurface geological successions from top to bottom
Tokar	Ashat	RS-01	Dry alluvial, weathered basement& fresh basement
		RS-02	
	Gabayab	RS-03	Alluvial& fresh basement
		RS-04	Alluvial& fresh basement
		RS-05	Alluvial, weathered basement
	Krembet	RS-06	Alluvial and deltaic deposits
		RS-07	Alluvial and deltaic deposits
		RS-08	Alluvial and deltaic deposits
	Farak Saleib	RS-09	Alluvial (sandy-clay) and deltaic sediments
		RS-10	Alluvial (sandy-clay) and deltaic sediments
		RS-11	
	Gadaeif/Khor Langeib	RS-12	Sand, clays, weathered and fresh basement
		RS-13	Sand, clays, weathered and fresh basement
		RS-14	Sand, clays, weathered and fresh basement
Sinkat	Shakan	RS-15	Clays, silt and weathered basement
		RS-16	Clay, sand and weathered basement
	Braseet	RS-17	Sand, clays and weathered basement
		RS-18	Sand, clays and weathered basement
	Asout Station	RS-19	Sand, clays and weathered basement
		RS-20	Sand, clays and weathered basement
	Tamay	RS-21	Sand, clays, weathered and fresh basement
		RS-22	Sand, clays, weathered and fresh basement
		RS-23	Sand, clays, weathered basement

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6. Conclusions

The application of geophysical methods helped in locating zones of enhanced secondary porosity such as weathered/fractured basement rocks. This is could be attributed to the application of the geophysical methods employed in this study has been combined with site geological and hydrogeological knowledge. The recognition of promising targets has been based on the prospective; Geological settings, Hydrogeological setting and the presence of recharge source.

In shallow basement areas of the investigated locations in the Red Sea State, electrical resistivity surveys, particularly HEP have revealed anomalies associated with low resistivity values (high conductivity), which is indicative for water-bearing zones. The successful detection of an anomaly has encouraged further through Vertical Electrical Sounding measurements. A total number of 23 VES using the Schlumberger configuration have been conducted in order to delineate the geo-electric layers in the targeted locations as well as to evaluate the groundwater potential in these locations.

Qualitatively, the dominant types of resistivity curves are KHQ and HKHQ curve types. Quantitatively, the interpreted subsurface layering and the corresponding lithologies reflects the subsurface configuration along the sets of vertical electrical sounding stations. The subsurface geological successions in the targeted locations of the Red Sea State delineated from the Quantitative interpretation of VES data.

The dominant aquifers in the investigated locations are encountered within; the weathered/fractured layers in the Basement Complex areas at the three localities of the Red Sea State where the aquifourous zones are characterized by resistivity values of (22 to 180 ohm m). Recent and quaternary alluvial/ deltaic deposits are covers huge area in Tokar locality of the Red Sea State. In these deposits the aquifourous zones are characterized by resistivity values of (35 to 82 ohm m).

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Data Availability Statement

All relevant data are included in the paper or its Supplementary Information.

Declaration Statement

The authors declare that the manuscript is original with no funding and competing interests-opposing. The article was not submitted or under investigation in other journal for simultaneous consideration. The authors have approved to publish the article based on the journal revelation.

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