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PREDICTION OF PROTECTIVE CAPACITY OF THE NUBIAN AQUIFER USING ELECTRICAL RESISTIVITY METHOD IN BAHRI CITY, SUDAN

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Abstract: This research employed vertical electrical sounding (VES) technique to determine the protective capacity of groundwater aquifers in Bahri city, Sudan. The protective capacity predicts the degree of vulnerability of the aquifers to surface and subsurface contamination. In the study, the product of inverted true resistivity and thickness were used to measure Dar Zarrouk parameters of longitudinal conductance and transverse resistance. Consequently, the longitudinal conductance-based protective capacity is used to assess the vulnerability of shallow and deep groundwater aquifers. In general, the protective capacity of the overburdened sediments ranged from poor to good. Accordingly, the aquifer in the study region is indicated as naturally protected and ideal for groundwater development.

Keywords: *Bahri, groundwater, Dar Zarrouk, VES, Nubian aquifer, protective capacity*

1. INTRODUCTION

Groundwater is one of the main sources of water supply in Sudan [1]. In order to meet the requirements for implementing development plans, the demand for groundwater in Sudan has increased dramatically [2]. Nonetheless, the increase in groundwater demand has posed various issues including over-exploitation and deterioration of groundwater quality [3, 4]. The decline of groundwater quality is a result of natural and human-induced activities such as urbanization and agricultural activities. Groundwater is naturally protected from contamination by the presence of aquitards and aquicludes however, shallow groundwater aquifers are susceptible to surface and subsurface pollution [5]. In regions where there is insufficient hydrogeological and hydrogeochemical data, the direct current electrical resistivity method can be applied efficiently to assess the aquifers characteristics and vulnerability to contamination [6, 7]. The geometry of the aquifers plays an important role in preventing groundwater aquifers from contamination since the thick impervious layers act as natural filters for groundwater aquifers. The electrical flow through subsurface layers is influenced by water content, shale volume, salinity of water, and porosity. The pores in soils and rocks permit contaminants to penetrate groundwater aquifers and alter the electrical, chemical, and physical characteristics of groundwater [8].

In this study, the geoelectrical vertical electrical sounding (VES) method is used to determine the vertical and horizontal extent of geological formations and predict the protective strength of groundwater aquifers. VES is a widely applied technique in hydrogeophysical investigations and it measures the vertical variation in electrical resistivity. Since electrical conductivity is proportional to groundwater salinity, VES can be successfully employed to detect contaminant plumes and thus determine the vulnerability of the aquifer to pollution. Inversion of the observed apparent resistivity data provides information on layer thickness and real resistivity. Maillet [9] was the first to establish Dar Zarrouk parameters utilizing actual resistivities and thicknesses to assess the longitudinal conductance and transverse resistance of layers. Additionally, Dar Zarrouk characteristics have been used to determine the susceptibility of aquifers to surface and subsurface pollution. The evaluation of the groundwater aquifer's protective capacity facilitates the identification of sensitive zones for contamination and also the creation of remediation plans [10]. Longitudinal conductance are widely used to assess the protective capacity of groundwater aquifers [11, 12]. For instance, Oguama et al. [13] integrated electrical resistivity tomography (ERT) and vertical electrical sounding to delineate groundwater potential zone and protective strength of groundwater aquifer. The study conducted by [14] proved the effectiveness of using longitudinal conductance to predict the vulnerability of groundwater aquifer in Belitung Islands Province, Indonesia. Akiang et al. [15] delineated the leachate and assessed the protective strength of groundwater aquifer in Calabar Flank, Nigeria.

From these studies, it can be indicated that the vulnerability of groundwater aquifers can be successfully assessed solely on geophysical data. Bahri area is agricultural land where chemical fertilizers and pesticides are extensively used. This research aims to employ vertical electrical sounding technique to determine the thicknesses of the subsurface sedimentary sequences and predict the vulnerability and protective capacity of groundwater aquifers. The outcomes of this research will highly contribute to the water management scenarios in the study area.

2. DESCRIPTION OF THE STUDY AREA

The region under study is situated in north Bahri city, Sudan *(Figure 1)*. The area is characterized by a hot climate with an average annual rainfall of 150 mm/year. Topographically, the area forms a peneplain with few ridges in the eastern parts. The most important geomorphological feature is the Nile River which limits the study area from the west. The geological sequence consists of three primary units *(Figure 2)*: Precambrian rocks, Cretaceous Nubian formation, and recent deposits. The basement rocks consist of gneisses, schists, and granites, and their depth ranges from zero, mostly in the northern and eastern parts of the region, to 500 m in the south [16]. The Precambrian basement is overlain by the Cretaceous Nubian formation [17].

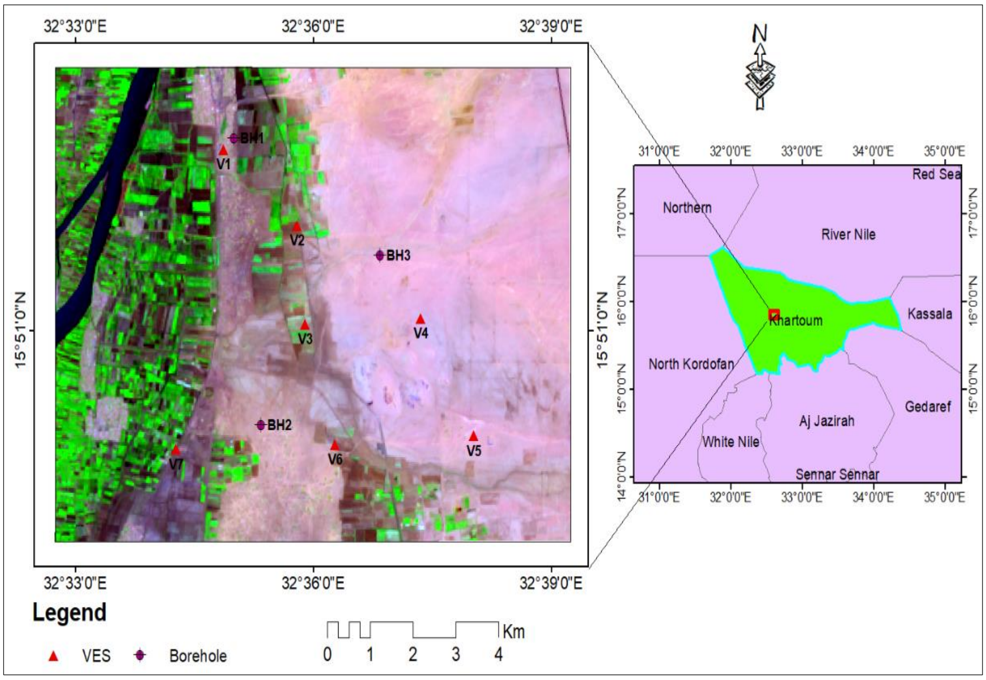


Figure 1

Geographical map showing the location of the study area in Khartoum state

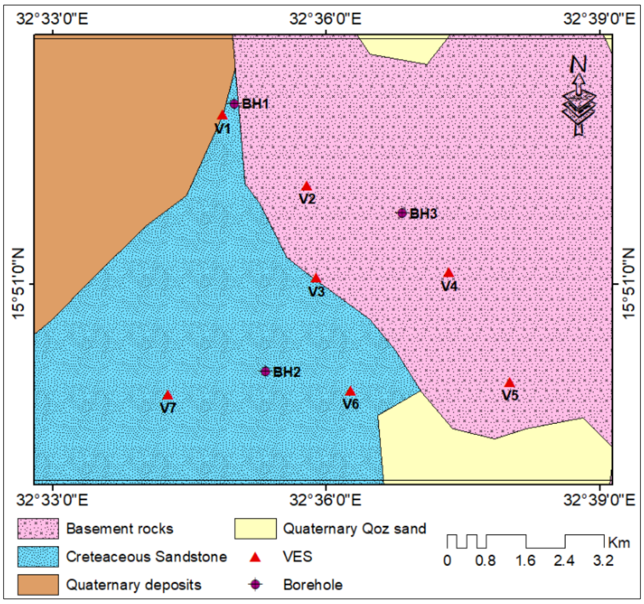


Figure 2

Geological map of the study area showing the main lithological units and geophysical sounding and drillhole locations

This geological formation is made up of conglomerates, sandstone, and mudstone [18]. The Nubian formation is the principal groundwater aquifer in the Khartoum basin. Recent deposits in the study region include wadi sediments and Qoz sand that were deposited by wind. These recent deposits consist of sand, gravel, and silt with depths ranging from 0 to 15 meters [19]. In the Khartoum basin, groundwater exists in the Nubian formation's poorly cemented sandstone strata confined to semiconfined settings. The aquifer is recharged from the Nile River and wadies [20].

3. MATERIALS AND METHODS

In this research, vertical electrical sounding with Schlumberger configuration is applied to characterize groundwater aquifers in north Bahri city. Seven VES points are performed with a 750-meter electrode spacing (AB/2). The schematic of Schlumberger array is illustrated in *Figure 3*. The measured apparent resistivity is processed using IPI2WIN program to determine the thicknesses and real resistivities of the geological succession. This approach applies the least damped square inversion by comparing the observed curve of apparent resistivities to a synthetic one calculated based on the estimated model. The acceptability of the final model is determined by fitness criteria between observed and computed data [21]. The IPI2WIN program utilizes the root mean square (RMS) error to represent the fitness or misfit of the curves. For an accurate interpretation of the geophysical model, it is necessary to gather priori information on the examined phenomena to avoid this limitation. This research uses lithological logs to verify the produced geoelectrical models.

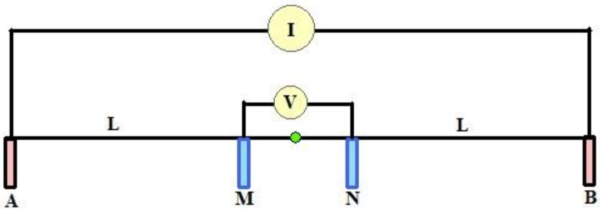


Figure 3
Schematic of Schlumberger configuration used for VES measurements

The notion of apparent electrical resistivity is based on measuring the potential difference between electrodes when electrical current flows through the earth's layers. The current and groundwater flow is influenced by the petrophysical parameters that govern the current flow, such as porosity, water saturation, and permeability [22]. Dar Zarrouk parameters, such as longitudinal conductance (S) in mho and transverse resistance (R) are based on the analogy between the movement of groundwater and electrical current. Dar Zarrouk parameters are a collection of layer thicknesses and actual resistivity that may facilitate the understanding of electrical models. The definition of Dar Zarrouk parameters is illustrated in *Figure 4*. In this research, the longitudinal conductance and transverse resistance are measured using as follows

$$S = \frac{h}{\rho} = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \quad (1)$$

$$R = h * \rho = \sum_{i=1}^{n} h_i * \rho_i \quad (2)$$

where h, ρ, and n are layer thickness, resistivity, and the number of layers, respectively.

The total longitudinal conductance and transverse resistance were used to evaluate the vulnerability of groundwater aquifers to surface and subsurface pollution by predicting the protective capacity of the aquifer. The protective capacity dictates the ability of the geological column to protect groundwater aquifers from pollution. In this research, the protective strength is assessed based on [23] classification which is mainly based on the longitudinal conductance of the subsurface layers. The highest longitudinal conductance indicates a thick layer and, hence, the best aquifer protection while the low makes aquifers susceptible to contamination [12, 24, 25]. Further, the transverse resistance is applied to confirm the obtained results.

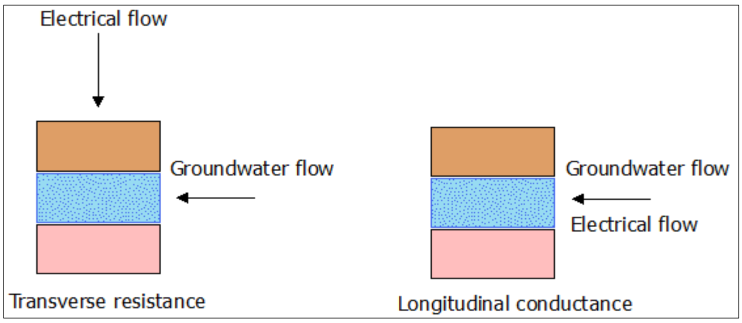


Figure 4

The principle of Dar Zarrouk parameters

Table 1

The protective capacity classes are based on [23]

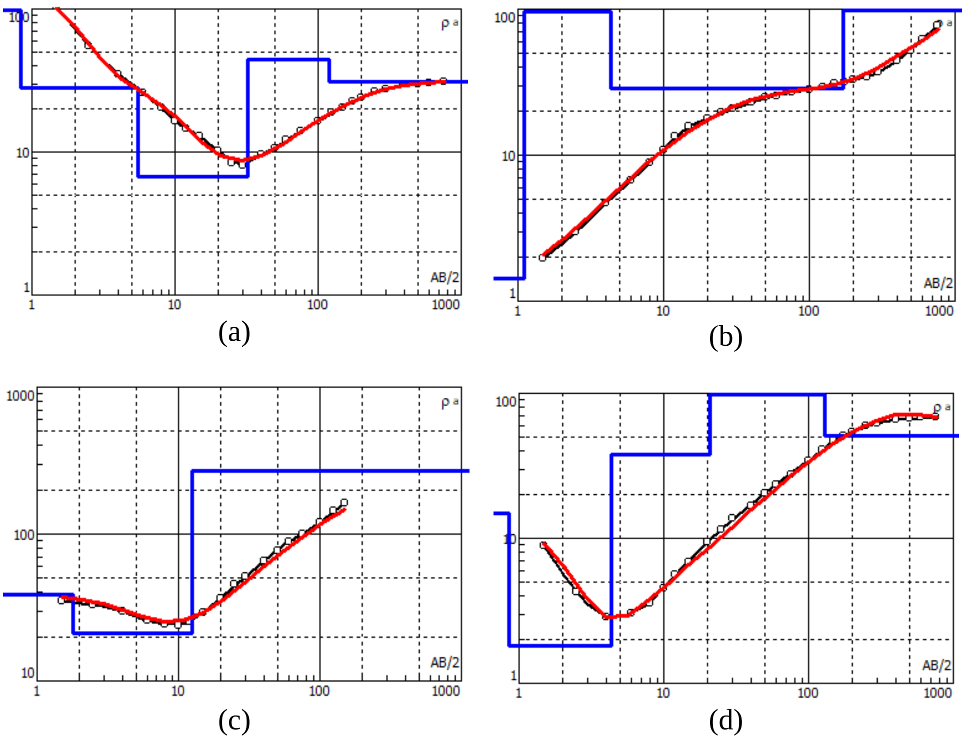
Protective capacity class	**Total longitudinal conductance (mho)**
Poor	<0.1
Weak	0.1–0.19
Moderate	0.2–0.69
Good	0.7–4.9
Very good	5–10
Excellent	>10

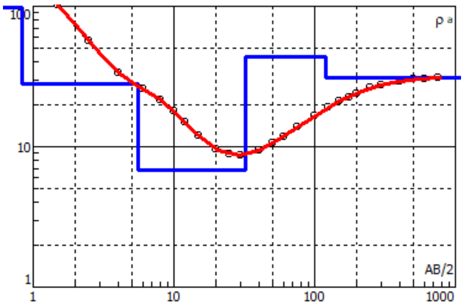
4. RESULTS AND DISCUSSION

4.1. VES interpretation

The aim of this research is to delineate the groundwater aquifers and predict the protective capacity of the hydrogeological column in Bahri city. This study analyzed seven VES measurements using a Schlumberger array to detect the thickness of the subsurface layers including groundwater aquifers. The apparent resistivity of the underlying materials is the measured parameter. To determine the thicknesses and real resistivities of the subsurface strata, this apparent resistivity is matched with master curves *(Figure 5)*. The curves were first qualitatively analyzed to get a general understanding of the distribution of electrical resistivity with depth. The thickness and number of layers that make up the model are revealed by the VES curves. To ensure accurate analysis of the sounding data, the obtained thicknesses and real resistivities are compared to the lithology of the closest boreholes.

Most of the VES curves integrated with the described logs revealed five layers. The layers are jointly correlated to their correspondence geological materials. Those layers consist of superficial deposits, clay, coarse sand, mudstone, and sandstone. The superficial deposits are composed of silt and sand [19] with an average resistivity and thickness of 100 Ωm and 1.7 m, respectively. A clay layer with an average thickness and resistivity of 18 m and 30 Ωm follows the superficial deposits. The third layer is saturated coarse sand. This layer represents the shallow aquifer in the study area under confined to semi-confined conditions. A mudstone layer with an average thickness of 80 m makes up the fourth layer. The mudstone layer divides the upper saturated layer from the lower one. Consequently, the fifth layer with an average resistivity of 140 Ωm is made up primarily of coarse sandstone.





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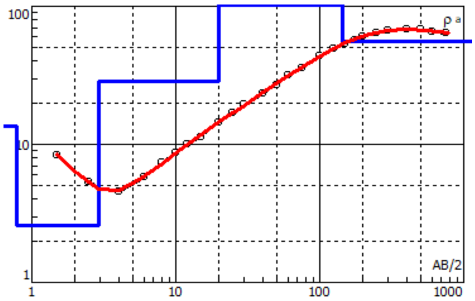

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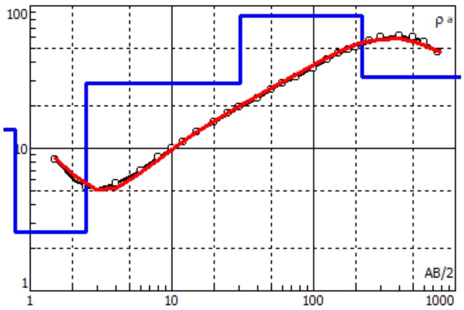

(g)

Figure 5

Result of VES measurements inversion for (a) VES1, (b) VES2, (c) VES3, (d) VES4, (e) VES5, (f) VES6, (g) VES7

4.2. Dar Zarrouk parameters

Dar Zarrouk characteristics are used to describe the protective capacity of groundwater aquifers in Bahri city. Transverse resistance and longitudinal conductance were measured based on the parameters derived from the geophysical inversion of the VES measurements. The results of VES inversion and the accompanying Dar Zarrouk parameters for each layer are shown in *Table 2*. In the research, the transverse resistance of the upper aquifer varies from 1638 to 8585 Ωm^2. The highest resistance is observed in VES 3 station where a high aquifer thickness is indicated while the lowest is in VES 7. The highest resistance indicates considerable thickness and high resistivity thus high potentiality [7]. The lowest value of transverse resistance does not always indicate low potentiality, but rather the presence of fine materials or a thin aquifer [26]. The longitudinal conductance of the shallow aquifer ranges from 0.24 to 1.2 Ω^{-1}. The largest value is recorded in VES 3, while the lowest value is found in VES 5. The largest value of conductance indicates high thickness and relatively low resistivity of the subsurface layers and vice versa. In this study, the low resistivity is an indication of the presence of clays and mudstone which increase the protective strength of groundwater aquifers. Since the depth of investigation is less than 500 m, the parameters of the lower aquifer cannot be estimated because the depth to aquifer bottom is higher than 500 m [27].

Table 2

Results of VES inversion and the derived Dar Zarrouk parameters

VES	Layer	h (m)	ρ (Ωm)	R (Ωm^2)	S (Ω^{-1})	PC (Upper)	PC (Lower)
1	1	2	119	238	0.02	Moderate	Good
	2	10	21	210	0.47		
	3	53	103	5459	0.51		
	4	22	41	908	0.5		
	5	–	129	–	–		
2	1	20	9	180	2.2	Good	Good
	2	66	103	6789	0.64		
	3	32	41	1312	0.78		
	4	–	129	–	–		
3	1	0.8	50	40	0.01	Moderate	Moderate
	2	5	11	55	0.45		
	3	101	85	8585	1.2		
	4	–	188	–	–		
4	1	3	106	318	0.02	Moderate	Good
	2	9	31	279	0.3		
	3	38	99	3762	0.38		
	4	98	26	2548	3.8		
	5	–	135	–	–		
5	1	1.4	124	173.6	0.01	Poor	Moderate
	2	3	51	153	0.05		
	3	27	112	3024	0.24		
	4	10	36	360	0.27		
	5	–	139	–	–		
6	1	0.9	114	102.6	0.007	Good	Good
	2	21	13	273	1.6		
	3	61	89	5429	0.68		
	4	24	32	768	0.75		
	5	–	163	–	–		
7	1	0.9	139	125.1	0.006	Good	Good
	2	13	10	130	1.3		
	3	21	78	1638	0.27		
	4	80	40	3200	2		
	5	–	122	–	–		

4.3. Protective capacity

This protecting capability of the subsurface materials is related to longitudinal conductance and inversely proportional to vertical and horizontal hydraulic conductivity [5]. The protective strength measures the ability of the geological columns to hold back surface and subsurface contamination. The protective capability of aquifers is presented in *Table 2* based on the categorization provided by [23]. The categorization of the aquifer's protective capability is based on the longitudinal conductance of the clay and mudstone layer.

The protective capacity of the upper aquifer is measured based on the geoelectrical characteristics of the upper clay layer. The longitudinal conductance of the clay layer ranged from 0.05 to 2.2 Ω^{-1}. The highest value is indicated in VES 2 while the lowest is observed in VES 5. Consequently, the protective strength of the upper aquifer is classified as poor, moderate, and good. The spatial variation in the protective strength classes is illustrated in *Figure 6*. The northern and eastern part of the study area is associated with good protective strength while the eastern parts are of poor to moderate capacity. The poor strength is due to the low thickness of the protective clay layer since the shallower aquifers are more susceptible to contamination than the deeper ones. The areas with low protective capacity considered is a pathway for the surface contamination which may later spread along the flow path and cause groundwater quality deterioration [15].

The protective strength of the lower aquifer is measured based on the parameters of the clay and mudstone layer. The longitudinal conductance varied between 0.4 to 4.1 Ω^{-1}. The greatest conductance is recorded in VES 4 where thick clay and mudstone layers are indicated while the minimal is indicated in VES 5 where the groundwater aquifer is close to the surface and covered by a thin clay layer. The geographical variation of the protective strength is shown in *Figure 7*. The capacity of the deep aquifer is categorized as moderate and good. Most of the study area is classified as of good strength. The deep aquifer exhibits protective strength higher than the shallow aquifer because it is completely under confined conditions with aquitards (Mudstone layer) of high thickness. These aquitards prevent the percolation of the contamination and reduce the vulnerability of the aquifer to pollution.

The overall protective capacity of the study area can be considered as good due to the restricted characteristics of the aquifers. The research region is agricultural land, however, agricultural operations have little impact on groundwater quality [28]. Agricultural practices that contaminate groundwater include irrigation, return flow and the application of fertilizers and pesticides. The aquifer's resistance to contamination may be explained by its protective capabilities. The geoelectrical method can be successfully applied for primary investigation of groundwater aquifer vulnerabilities. However, detailed groundwater quality studies and monitoring is required for sustainable management of groundwater resources.

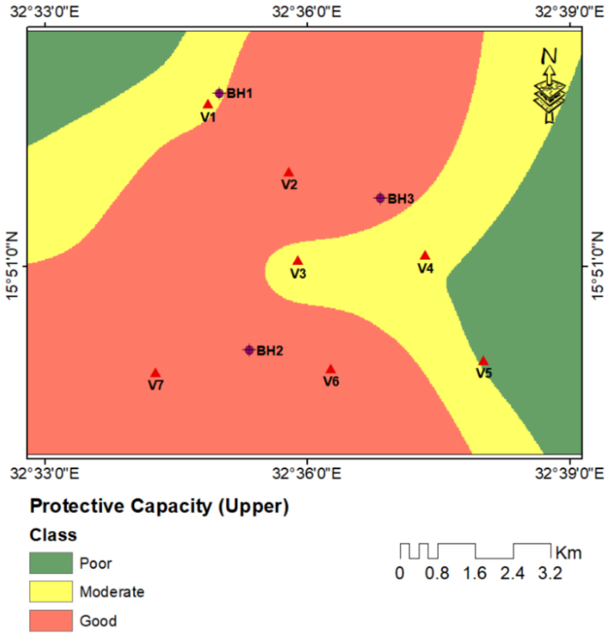

Figure 6

The areal distribution of protective capacity of the shallow (upper) aquifers

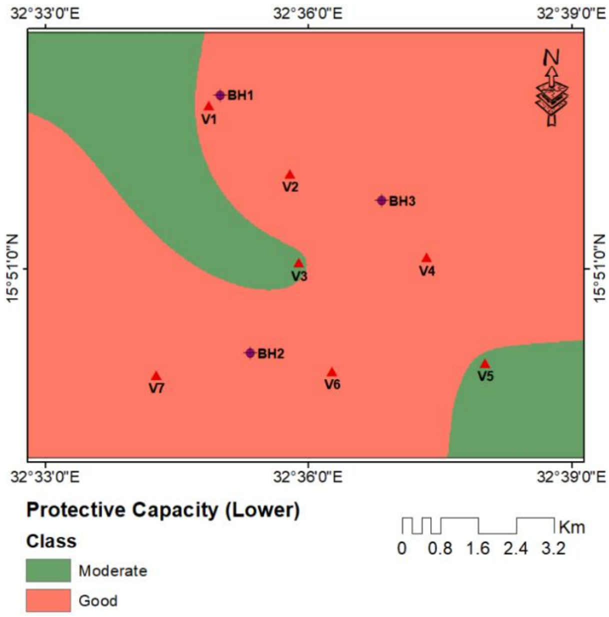

Figure 7

The areal distribution of protective capacity of the deep (lower) aquifers

5. Conclusions

In this research, vertical electrical sounding technique using Schlumberger electrode configuration is applied to delineate the subsurface lithology in Bahri city and predict the protective strength of the groundwater aquifers. The apparent resistivity is processed using a 1D geoelectric inversion approach to obtain the true resistivities and thicknesses of the subsurface layers. The sounding data were combined with lithological records for a reliable interpretation of VES results. According to the findings, the research region consists of two aquifer systems. The top aquifer is comprised of coarse sand, whilst the lower aquifer is composed of coarse sandstone with considerable thickness. Additionally, Dar Zarrouk characteristics were utilized to determine the aquifers' protective capacity. Longitudinal conductance and transverse resistance were measured using the true resistivity and thickness obtained from geophysical inversion. The protective capacity of the upper groundwater aquifers ranged from poor to good while for the deep aquifer it categorized as moderate and good because of the high thickness and low permeability of the surface layers. Consequently, the overall protective capacity of the aquifer reflected that the aquifer is protected from surface and subsurface pollution, and therefore, groundwater with high quality is likely to be stored. However, this study recommended a detailed hydrochemical analysis for the evaluation of groundwater and its suitability for human consumption. This research further recommended a detailed geophysical survey to accurately detect the thickness of the subsurface strata.

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