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Geo-electrical and Hydrogeological Investigation of Khor Adeit Basin Aquifer, Sinkat Locality, Northeastern Sudan

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Abstract— **In this study Sub-surface geo-electrical resistivity survey using vertical electrical sounding (VES), in addition to hydrogeological investigation, were employed to characterize the hydrogeological setting and to determine the hydraulic properties of the aquifer system of Khor Adeit basin in the Red Sea State in eastern Sudan. Sixty five (VES) were conducted in the stream channels using Schlumberger array configuration. The data was interpreted using the conventional curve matching and computer iteration method. Eleven well logs were studied to explain the lithology of the aquifer. The results revealed three subsurface geo-electric zones; from top to bottom these are: Unsaturated, saturated and non-water-bearing zones. The saturated zone which represents the aquifer consists of fine, medium to coarse sand and the weathered basement rocks. It is characterized by resistivity values of 10 to 90 Ω.m and a moderate thickness of 15 meter. The saturated zone underlain by the basement complex rocks, a non-water-bearing unit which has high resistivity values of 1320 to 9329 Ω.m. The geo-electric findings are in compliance with lithological logs of boreholes. The aquifer is unconfined to semi unconfined. Depth of water table varies from 9 to 30 meter. Groundwater flow is from south to north. Aquifer parameters are variable because of the heterogeneity of the aquifer composition. It is found that the transmissivity ranges from low 66m^2/d to high 1898 m^2/d, whereas the hydraulic conductivity ranges from small 4 m/d to moderate 137m/d and the effective porosity has values between 0.2 and 0.4.**

Index Terms— **Groundwater, Hydrogeological setting, Sinkat, Red Sea State and Vertical electrical sounding.**

I. INTRODUCTION

The study area comprises the basin of a seasonal water course called Khor Adeit. It originates from the southern part of the Red Sea Hills Series, and flows across a small town named Sinkat which lies 120 km south west of Portsudan –the capital of the Red Sea State (RSS)- in eastern Sudan. The study area is bounded by coordinates: 36°45´E / 36°55´E and 18°45´N /19°00´N, (Fig. 1). It covers an area of 532 square kilometer. The area of the study is characterized by semi-arid climate with annual mean rainfall of 100mm, and high evaporation where potential evapotranspiration (PET) was estimated to be between 1500 and 2400 mm [1], [2].

Groundwater and surface water which harvested from seasonal water courses both represent the main source of freshwater in the area. In the last decades these sources were deteriorated and depleted due to intensive use of water especially in summer time due to tremendous increase in residents, because the area has an advantage of temperate weather compared to its surrounding and being a center for cultural activities and tourism. In addition, there is an increasing demand of water for agriculture and livestock.

The most widely used geophysical methods in hydrogeology are the electrical techniques; the resistivity method is the most popular of all the electrical techniques [3], [4]. Vertical electrical sounding (VES) is a geoectrical common method to measure vertical alteration of electrical resistivity. This method has been recognized to be more suitable for hydrogeological survey of sedimentary basin [5], [6]. [5] also stated that, there are approximately one hundred independent geoelectric arrays, but Schlumberger array is found to be more suitable and common in groundwater exploration. One of the fundamental aspects of groundwater resources investigations is the determination of the aquifer characteristics of permeability and storativity values [7].

Increase of water resources in the study area to meet the ever growing demand is becoming very essential. Hence application of hydrogeological and geophysical methods in prospect areas could definitely push in this trend. In this context, this study is aiming at the characterization of the hydrogeological setting and determination of hydraulic properties of the aquifer system as keywords for groundwater resource evaluation and development.

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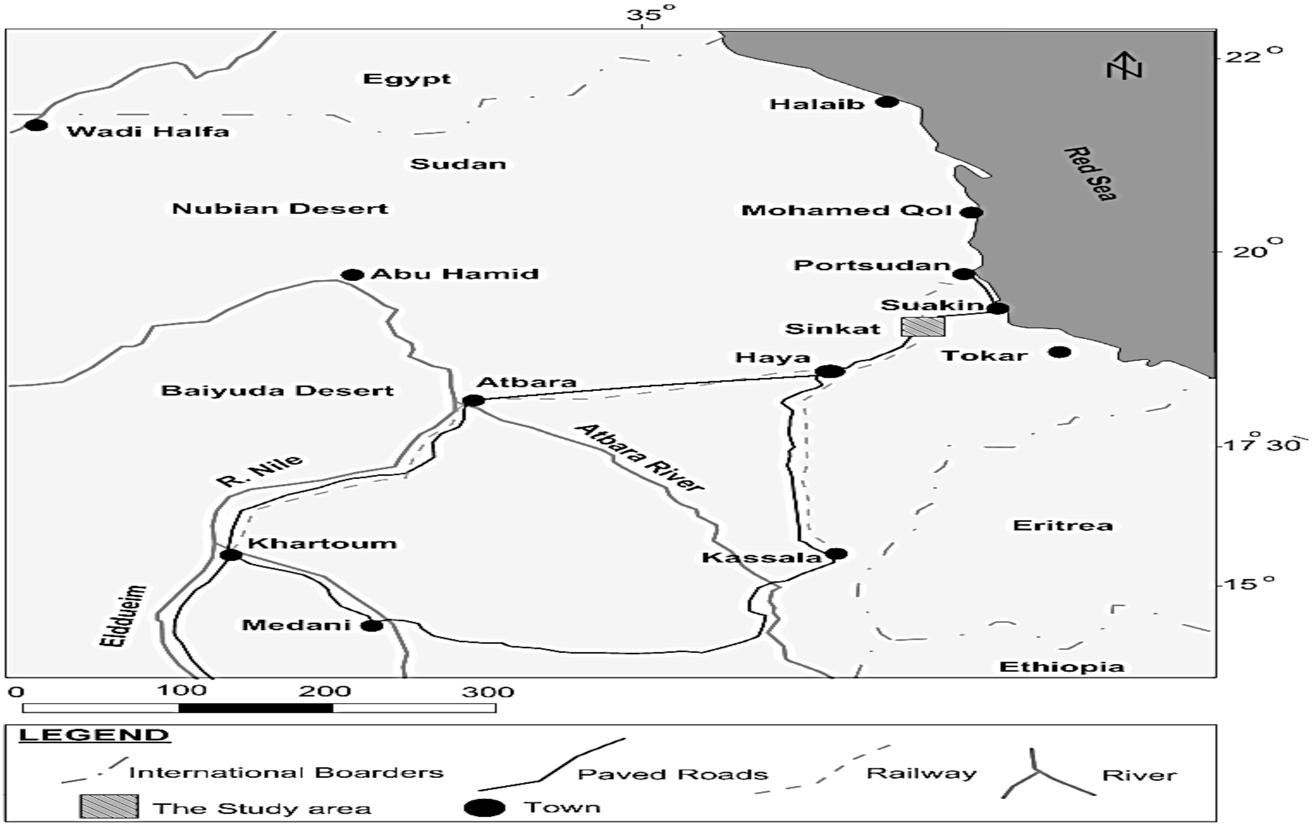

Fig.1: Location map of the study area and means of accessibility.

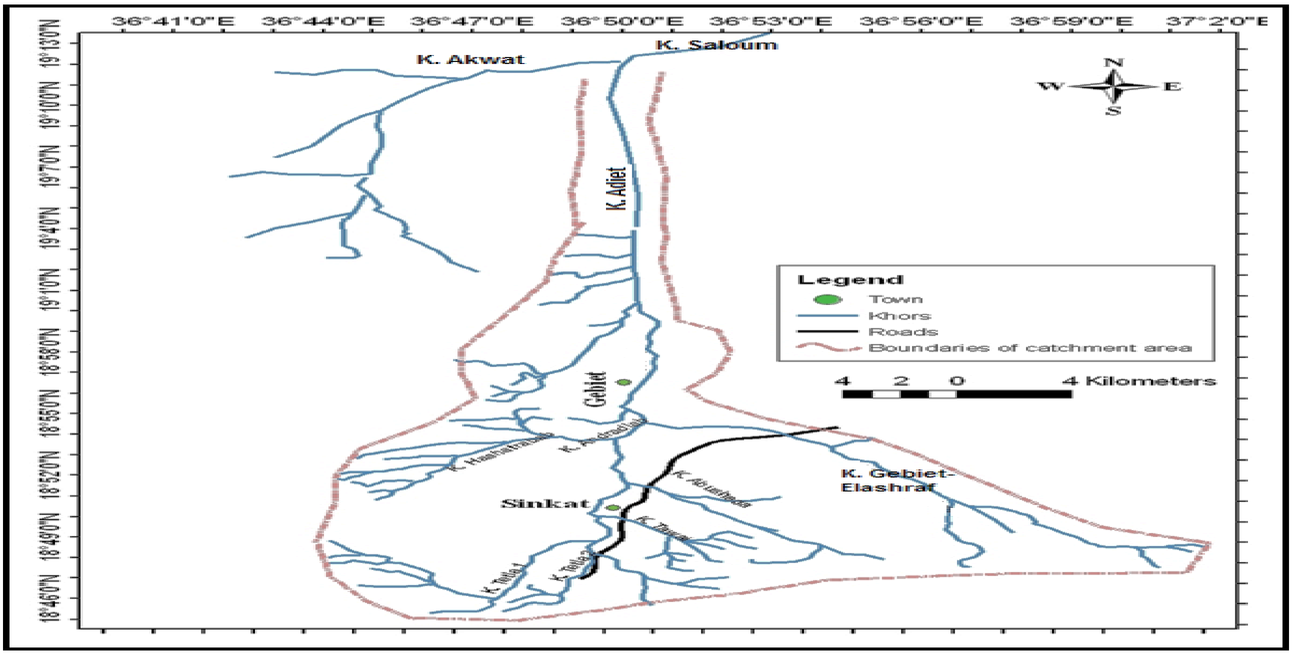

Fig.2: Drainage basin of Khor Adeit.

II. GEOLOGY

The geology of the study area is mainly controlled by the regional geologic and tectonic settings of the Red Sea region [8]. The lithostratigraphic sequence comprises of the Pre-Cambrian basement rocks and Phanerozoic sedimentary cover of age Quaternary to Recent [8], [9], [10]. The basement rocks comprise of meta-volcano sedimentary sequences (900-650Ma), batholithic complex, intrusive massifs, and dyke swamps [8],[11], [12], [13]. Phanerozoic sedimentary cover includes alluvial sediments deposited by the drainage system, they rest unconformably on the Precambrian basement rocks. The alluvial sediments mainly consist of silt, fine to medium-sized coarse sand and gravels. Geological map of the study area is depicted in (Fig. 3).

III. METHODS AND TECHNIQUES

Geoelectric measurements and hydrogeological investigation were employed to achieve the objectives of this study. A geological reconnaissance was carried out to determine the various geological units of the study area. Geoelectric survey has included 65 vertical electrical soundings (VES) was conducted along the channels of Khor Adeit and tributaries to delineate the areal extent and thickness of the aquifer. Schlumberger array was adopted with a maximum spread distance (AB/2 =200m) to measure apparent resistivity at these (VES) points. The interpretation and analysis of apparent resistivity field data was done using IPI2win and Resix^{plus} computer programs. The hydrogeological investigation included well and boreholes inventory using GPS for well location and water levels indicator to measure water levels. Lithological logs of 11 wells were used to predict the lithology of the aquifer. To study aquifer composition and characteristics, grain-size analysis was performed for four aquifer samples collected from four boreholes, at a depth varies between 28m and 50 m. Also test pumping was carried out to determine aquifer characteristics. Pumping test as a method for computation of aquifer parameters has been described by many authors e.g. [14], [15]. [16]. The data obtained from test pumping were run in the computer using Infinite Extent version 3.2 and AQTESOLV version 3.01.004 software. Arc-Map version 9.3 & Free-Hand programs were used for maps production. The locations of the borehole and the VES points are shown in Fig. 4.

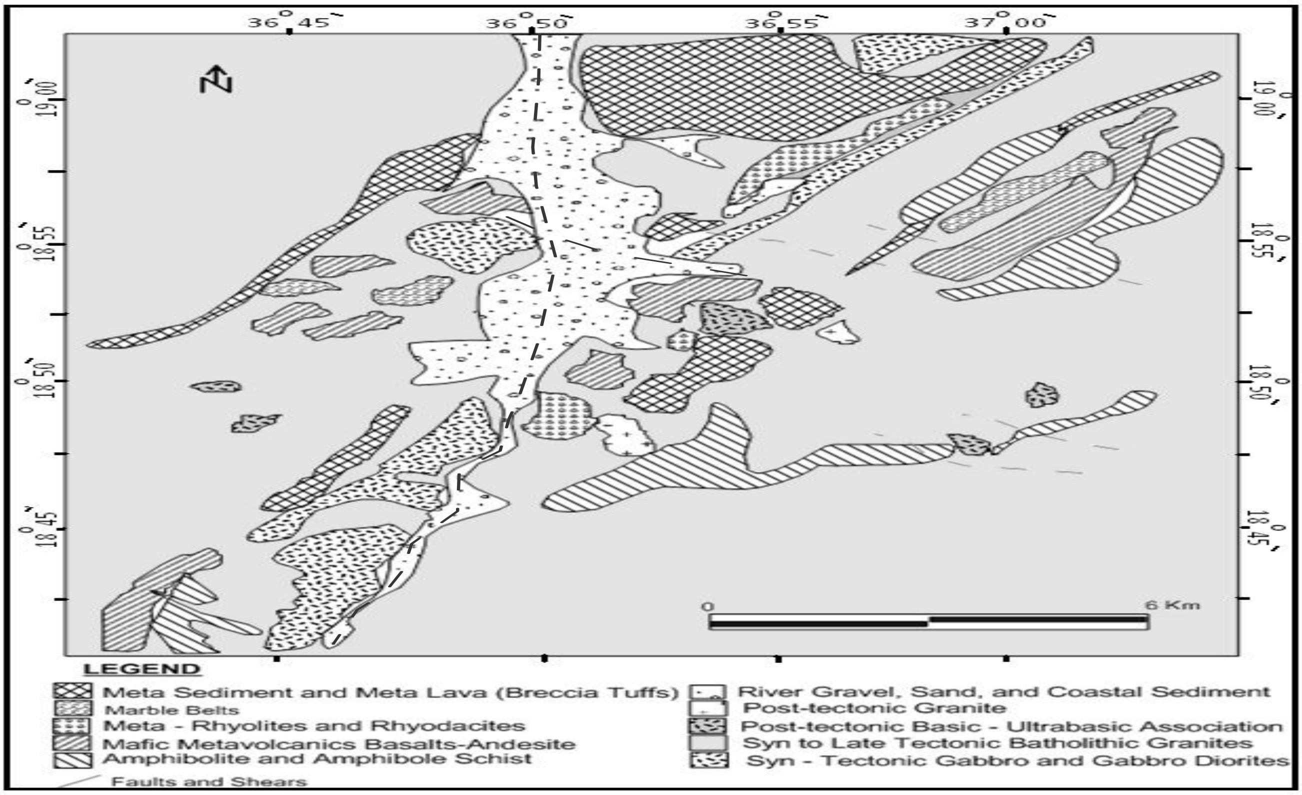

Fig. 3: Geological map of the study area.

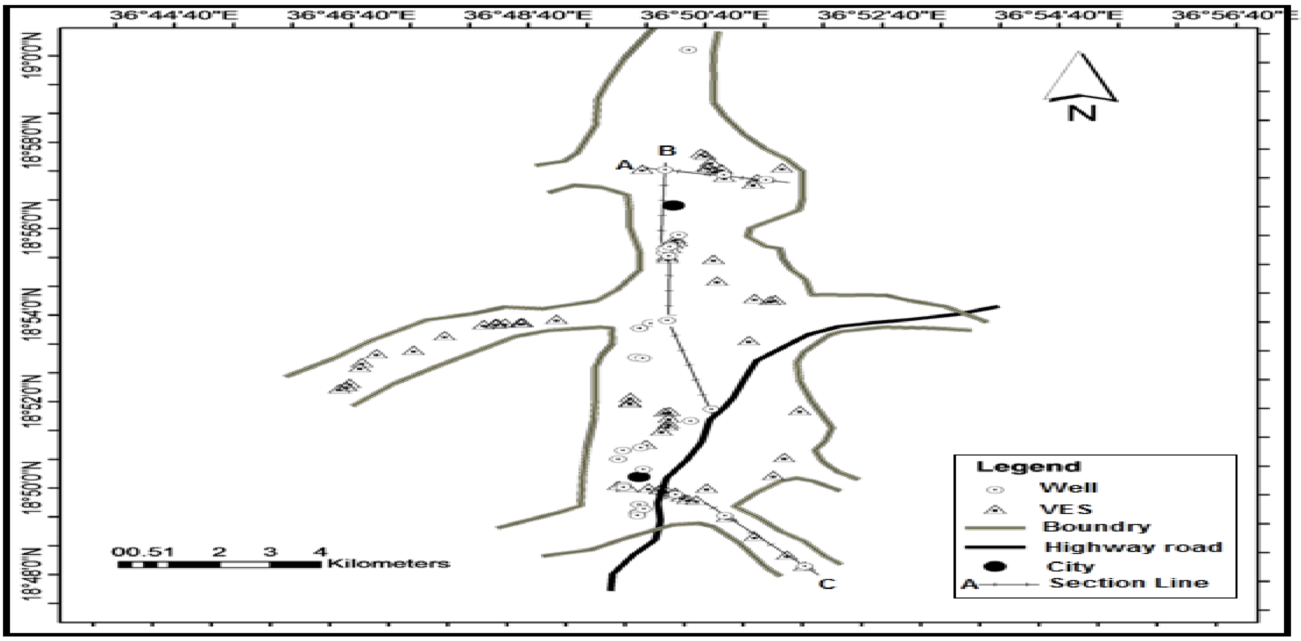

Fig. 4: Location of VES points, boreholes and geological section lines.

IV. RESULTS AND DISCUSSION

1. *Aquifer System*

Interpretation of geo-electric data revealed three subsurface geo-electric zones; from top to bottom these are:-

- Unsaturated layer starts from ground surface up to the depth of the water table which varies from (9 to 30m.b.g.s). It mainly consists of two to three layers of wide range of resistivity values between 25 Ω.m and 787 Ω.m.

-Saturated zone starts at the depth of water table ( ) to the basement rocks at depth of 37 to 60m.b.g.s. with varied thickness of 10 to 30m. This zone marked by resistivity values of (10 to 90 Ω.m).

-Non water-bearing zone which is characterized by high resistivity values of 1320 to 9329 Ω.m. it comprises of crystalline basement rocks.

The aquifer system in the study area basically consists of the Quaternary to Recent alluvial deposits of the Adiet basin, and often the aquifer extends to include the upper most fractured and weathered basement rocks. Areal extent and saturated thickness of the aquifer were estimated from the boreholes data and the above geo-electric findings; the thickness was found to be between less than 7m and more than 30m with an average value of 14.7m. Whereas the area occupied by the aquifer is approximately 7.8 square kilometer. Fig 5 shows geo-electric curves and their interpretation in comparison with borehole lithological logs, while Fig. 6 reveals the aquifer thickness.

Four sample curves of sieve analysis results were shown in Fig. 8. The effective grain size (d_{10}) of the aquifer materials ranges between 0.18 mm and 0.25 i.e. it is between very fine to fine sand. Values of the coefficient of uniformity (Cu) range from 4 to 12 indicate that sediments are rather uniformly graded, and could be grouped into four classes; silty very fine to fine sand, medium to Coarse sand with pebbles, Pebbly sand and Sandy gravel. Fig. 7 shows the three geological cross sections which their locations were shown already in Fig. 4. It was recognized that the facies change abruptly both laterally and vertically and this was attributed to the changing conditions of sedimentation.

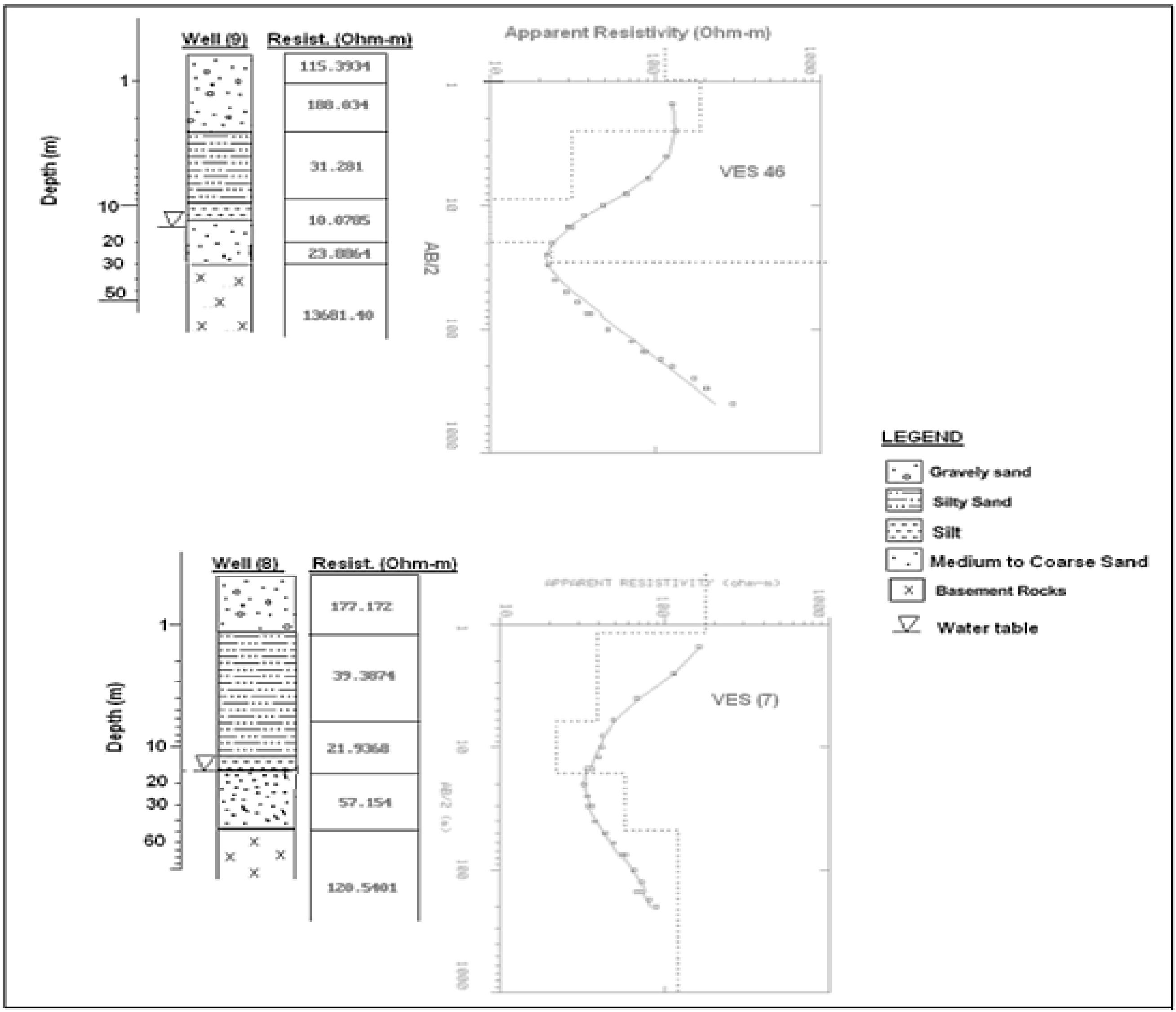

Fig. 5: Interpretation of geo-electric curves compared to borehole lithological logs.

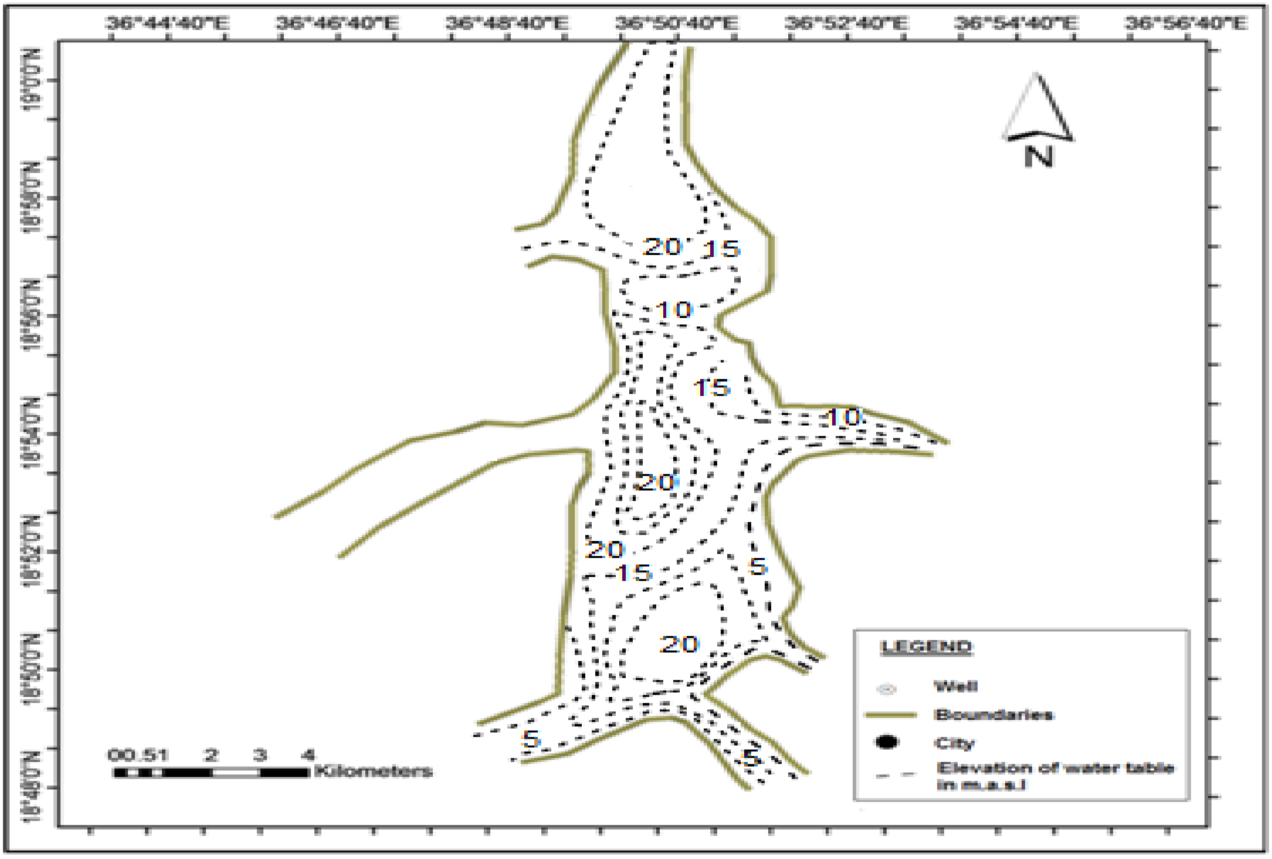

Fig. 6: Aquifer thickness map as determined by VES method.

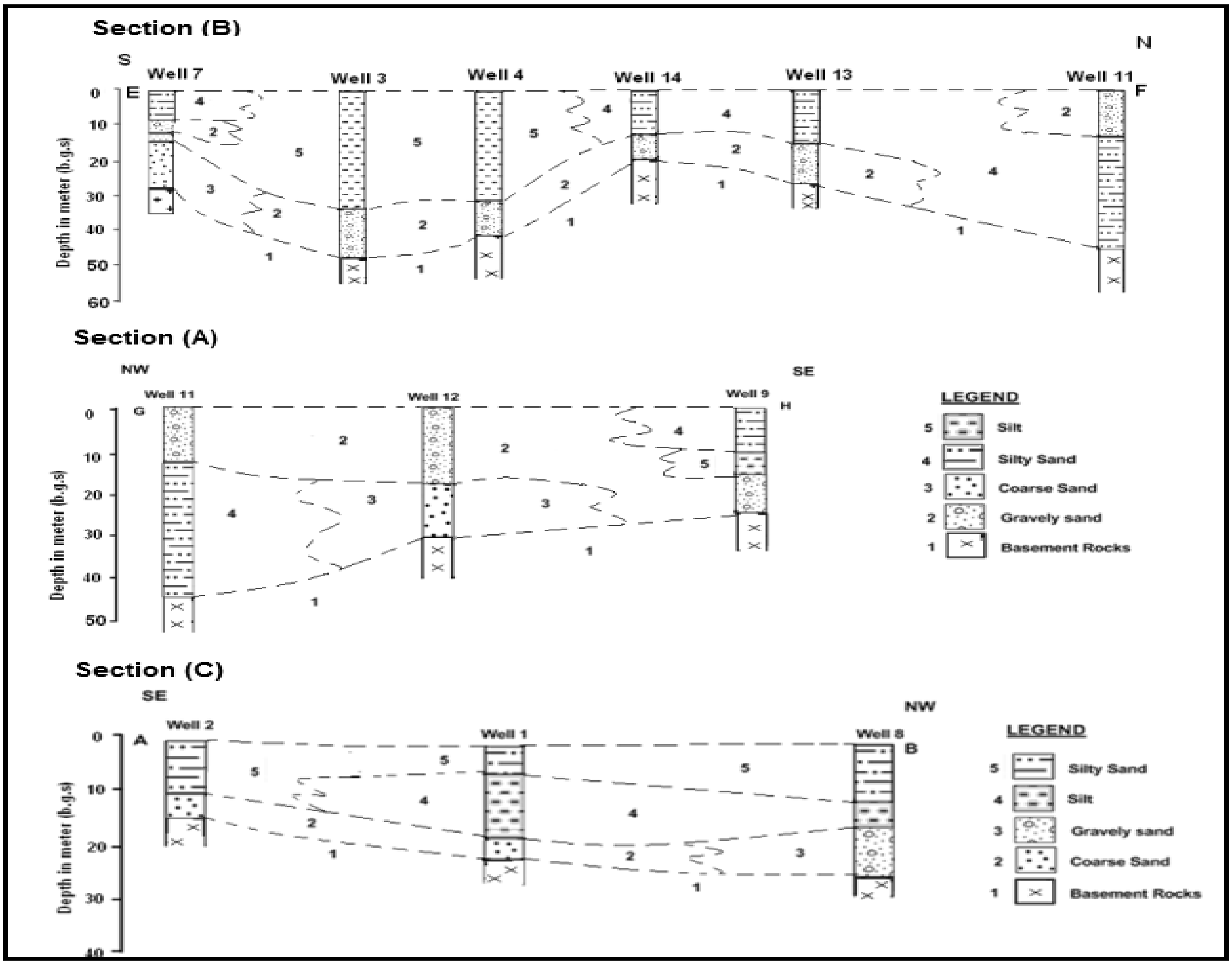

Fig.7: Geological cross-sections.

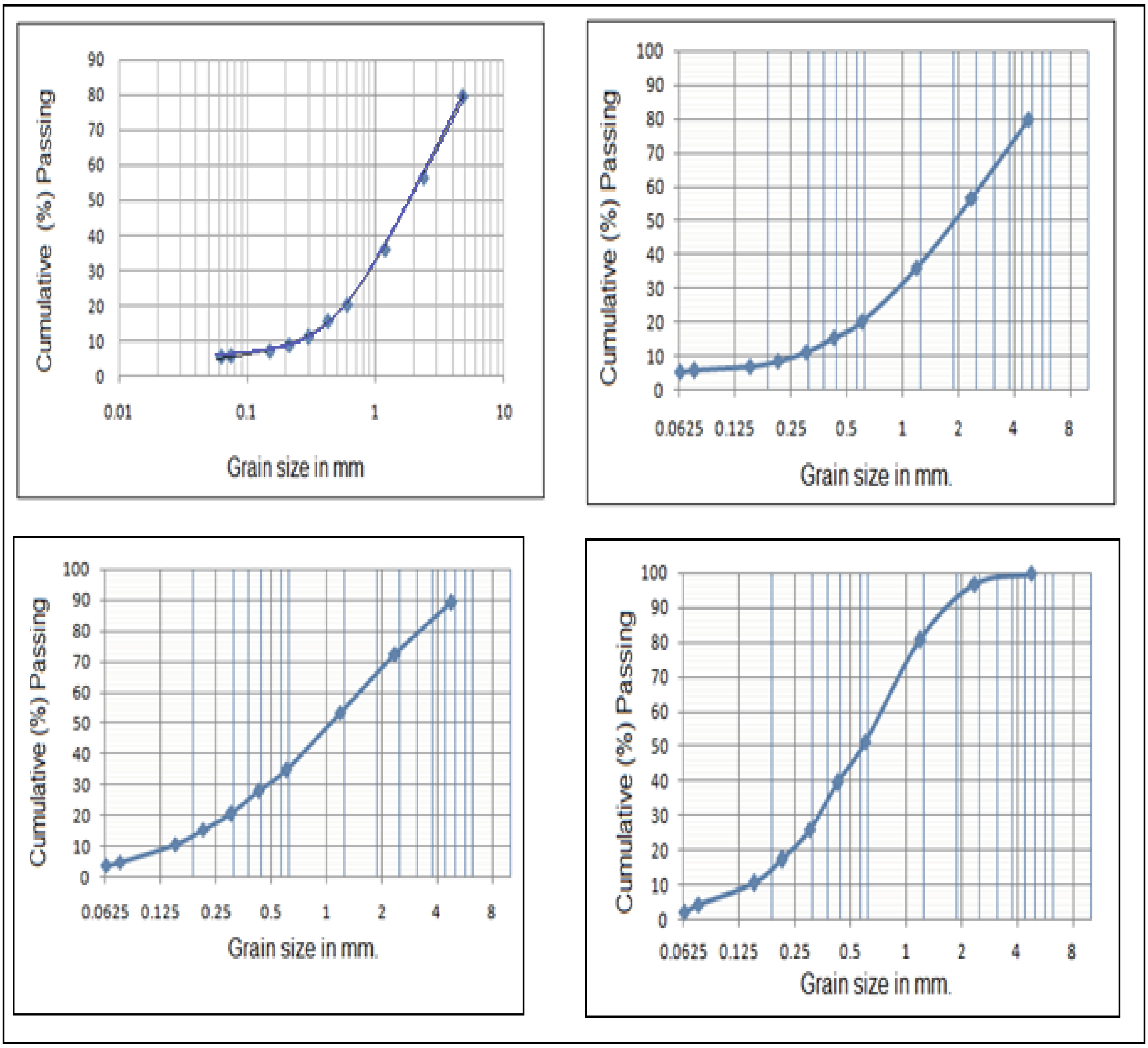

Fig. 8: Samples of grain size distribution curve showing well graded samples.

2. *Aquifer Characteristics*

Since pumping tests are not available for large parts of the aquifer; the aquifer characteristics have been determined using two different methods for comparison and confirmation. These namely are:

2.1. Grain size analysis

The Hydraulic conductivity (K) has been determined in 6 locations by means of grain size analysis using Hazen's and Kozeny-Carman-Bear equation [17], and then the transmissivity (T) was calculated by multiplying the obtained values of (K) by the saturated thickness.

$$K = \left[\frac{\rho_w \cdot g}{\mu}\right] \times \left[\frac{d^2}{180}\right] \times \left[\frac{\text{Ø}^3}{1-\text{Ø}^2}\right] \ldots\ldots\ldots..(1)$$

where K is hydraulic conductivity in m/d, ρ_w is the fluid density taken to be 1000 kg/m^3, g is gravitational constant in m/s^2, μ is the dynamic viscosity assumed as 0.0014 kg/m^3, *d* is any representative grain size which assumed as 0.001875m, and Ø is the porosity of the medium with an average value of 0.36.

The calculated values of K vary from 0.82 m/d to 6.31 m/d with an average value of 3.68 m/d; and T values vary between 11.48 m^2 / day and 108.53 m^2 / day with an average value of 64.44 m^2 / day

2.2 Pumping Test Data Analysis

The analysis of pumping test data to estimate aquifer characteristics is normally achieved by the application of various formulas. The methods have been adopted to analyze pumping test data in the study area were stated in [18], [19], [20] and [21], using recent software namely Infinite Extent and AQTESOLV programs. The pumping test findings were given in Tables (I, II and III). The aquifer system in the area has varied transmissivity ranges from (10 to 129) m^{2}d^{-1}, hydraulic conductivity from (2 to 18) md^{-1} and specific yield from (0.036 to 0.269)

Table I: Hydraulic parameters obtained from pumping test data analyses (Hydraulic Conductivity in m d^{-1})

Well No	Location	Theis Method	Jacob-cooper	Neuman	Theis recovery	Logan	Arth. mean
1	Tawai	4.1	6.8	2.8	7.8	1.8	4.7
Elwsam	Adiet	5.7	4.7	4.8	5.4	7.4	5.6
Military	Adiet	4.2	4.2	2.1	-	6.1	4.2
5	Andradiab	-	4.1	-	2.4	1.44	2.65
6	Andradiab	-	-	-	3.11	-	3.11

Table II: Hydraulic parameters obtained from pumping test data analyses (Transmissivity in m^2d^{-1}).

Well No	Location	Average Thick (H), m	Theis Method	Jacob-cooper	Neuman	Theis recovery	Lagon	Arth. mean
1	Tawai	10.13	41.4	69.98	29.02	81	19	48.08
Elwsam	Adiet	17.4	98.33	80.99	83.08	93.5	128.9	96.96
Military	Adiet	17.5	73.5	73.5	36.32	-	107	72.58
5	Andradiab	-	-	85.68	-	50.4	30.02	55.37
6	Andradiab	-	-	-	-	57.1	-	57.1

Table III: Hydraulic parameters obtained from pumping test data analyses (Specific yield).

Well No	Location	Theis Method	Jacob-cooper	Neuman	Theis recovery	Hantush	Arth. mean
1	Tawai	0.036	-	0.036	0.122	-	0.07
Elwsam	Adiet	-	0.234	0.1	-	0.224	0.19
5	Andradiab	0.1	0.1	-	-	0.269	0.16

Test pumping in the study area show low to moderate values of aquifer parameters, because some of the pumping test assumptions were not satisfied such as the pumping well should fully penetrate the aquifer thickness which was not always the case and there were no observation wells in the study area, so that all measurements of water level were carried out in the pumping wells. This let taking measurements sometimes difficult and not precise. On the other hand, the grain size analysis method shows low, moderate to very high values of aquifer parameters; the very high values are attributed to presence of coarse sand and gravel; whereas the low values are related to fine and medium sand or silt.

3. *Groundwater flow regime*

For schematic representation and understanding the groundwater flow regime in the study area, a water table contour map was prepared Fig. (9).

The great difference in depth to water table, attributed to many reasons such as variation in depth to bed rocks, heterogeneity and anisotropy of the aquifer, and the presence of earth dams across the stream channels which have noticeable impact on groundwater levels particularly in the adjacent areas. The groundwater flow direction is generally parallel to the Khor Adiet course and its tributaries from south, southwest to north, northeast.The hydraulic gradient is ranging between 0.00026 and 0.002, with an average value of 0.0012.The steep gradient in the area might be attributed to low transmissivity as a result of presence of fine material, whereas wide groundwater contour spacing in the central part indicates high transmissivity than other parts of the aquifer. Velocity of groundwater is about 230m/year.

V. CONCLUSION

The aquifer of Adiet basin is unconfined to semi unconfined and structurally controlled; bounded from left, right and bottom by crystalline basement rocks. The thickness of the aquifer is varied from (10 to 30 m) with greatest thickness at the axial trough of the stream channels. The depth to water-table is varied from (9 to 30 m.b.g.s); shallow at Tawai-Tetia–Sinkat area and deep at Andradiab-Adiet area. The aquifer system in the area has transmissivity ranges from (66 to 1898) m2d-1, with an average value of 982 m2 / day, Hydraulic conductivity from (4 to 137) md-1 with an average value of 70.5 md-1 and storativity from (0.0064 to 0.233) with an average value of 0.136.

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