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Integrated Formation Evaluation of Quaternary Aquifer in Assiut Governorate, Nile Valley, Egypt, Based on Vertical Resistivity Soundings and Well Logging Analysis

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Abstract

Groundwater resources are gaining much attention with increasing demands for water due to increasing population, urbanization and agricultural expansion in Egypt. First objective of this paper is to interpret Vertical Electrical Soundings (VES) in a number of stations covering Assiut Governorate to assess the geometry of the Quaternary aquifer (QA). The VES interpretation covered the determination of depth, thickness and true resistivity of the geoelectrical layers and then picking the water bearing layer (aquifer). The VES interpretation reflects the outstanding role of QA variation in the studied area. Second objective is to use open-hole logging data from 52 wells for determining the detailed reservoir characteristics to evaluate the hydrogeologic and petrophysical parameters of the aquifer. The well log analysis procedures are performed in different phases led to formation evaluation using specially designed program utilizing the level by level technique.
Accordingly, the QA petrophysical parameters including the total, effective porosity, shale content, permeability, lithology, Bulk Volume Water (BVW), water salinity and net pay presented in the form of litho-saturation cross-plots and distribution maps. Such parameters are useful in case of subjecting the area to modeling or GIS studies. Correlation of results indicates that the QA thickness decreases gradually towards the fringes. Total porosity values vary from 23.77% to 39.76%, and the effective one from 21.16% to 38.46%. The calculated permeability values reflect high quality of the studied aquifer. Furthermore, the estimated low shale volumes (4.48 to 25.88%) and high sand volumes (45.59% to 65.62%) of the water-bearing horizons confirmed the good quality of the aquifer. Total dissolved solids (TDS) are in the range from about 400 to 1000 ppm, which indicate fresh type of groundwater.

Keywords: Vertical Electrical Soundings, Reservoir Characterization, Well logging, Formation Evaluation, Groundwater Resources.

Introduction

The Quaternary Aquifer system (QA) is a renewable, highly productive and generally contains easily accessible fresh water that is used for drinking and irrigation where its salinity is below 1000 mg/l. The study area is located in Assiut Governorate and extends from 26° 47′ -27° 37′ N, and 30° 37′ -31° 34′ E, about 125 km long and 60 km wide, occupying both populated and agriculture areas [1]. QA is the most important water resources necessary for development and reclamation in Assiut Governorate.

The current work aims at determining the geometry and conductivity parameters of the Quaternary aquifer (QA) using conducted VES'es, as well as evaluating the detailed hydrogeologic and petrophysical characteristics of the QA, using well logging data in Assiut area which are important in sustainable developments.

Geomorphology and general geology

Because of its importance, the QA has long been subjected to comprehensive geological studies. Examples of these are [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16] and others.

The old and cultivated land, cover an area of about 2500 km² (Fig. 1). River Nile splits the study area longitudinally into western and eastern parts. The western part is larger than the Eastern one, where its area is about 1500 km² (Fig. 1). Land surface in the fringes of each part is generally slopes towards the River Nile. A gradual slope to the north is also a remarkable feature. The study area covers most of the cultivated land either old or recently reclaimed. The sharp declination is the dominant feature of the fringes of the study area because of the limestone plateau which bounds the area from the east and the west, except for the northwestern part, which has a gentle slope (Fig. 1).

The QA occupies the most part of the Nile valley, which is bounded by the limestone plateau from the east and west, extending along the study area and most of the Nile valley. A silty clay cap covers the most surface of the QA and occupies the central part of the aquifer. Except for the fringes, QA hasn't any outcrops, which are wide in the central part and very narrow at the northern and southern parts of the study area, except Wadi Abu Shih in the south (Fig. 1).

Generally, the rocks cropping out in the studied area are all of sedimentary origin, and belong to the lower Eocene, Plio-Pleistocene and Holocene (Fig. 1). This aquifer varies in thickness from about 280 m around Manfalut city to about few meters and zero at the fringes.

Data and Techniques

The previously executed VES'es curves [17] using Schlumberger configuration [18] and covering the study area were collected (Figs. 2 and 3), analyzed and reinterpreted using the Russian IPI2DW Software [19] (Fig.4).

The log data from the available 52 wells (Fig.5) were environmentally corrected, normalized, and linked relationally in the GIS to be viewed and processed in spatial context. Well logging tools, which are considered the most important and widely used in the field of hydrogeology are self-potential (SP), shallow and deep resistivity (R16" & R64"), gamma ray (GR) , and neutron (ΦN) logs.

Information about the basic principles of log analysis is found in many publications, e.g. [20], [21], [22], [23], [24], [25], [26], [27], and others.

The log data have been subjected to a comprehensive analytical formation evaluation using a special approach [28], which was assembled on the basis of the Czech computer software (SG system) [29]. The evaluation consists of the level by level calculation of true resistivity (Rt), formation water resistivity (Rw), shale volume (Vsh), total porosity (ϕT) , effective porosity (ϕe), water saturation (Sw), as well as the net pay parameters (bulk water volume "BVW"). The steps of processing and interpretation of the data using the above mentioned algorithm (Fig. 6) are briefly described as follow.

1. Shale Volume Determination

The volume of shale can be calculated using single indicators, e.g. gamma ray, SP, Neutron or resistivity logs:

From Gamma-Ray

Gamma-ray log has sensitive response for the radioactive materials normally concentrated in the shaly rocks. The following equation is used to determine the Gamma-ray index [20]:

$$I_{GR} = (GR_{log} - GR_{min})/(GR_{max} - GR_{min}) \quad (1)$$

where: I_{GR} is the Gamma-ray index ,
GR_{log} is the Gamma-ray reading for each zone, and GR_{min} and GR_{max} are the minimum Gamma-ray value (clean sand or carbonate) and the maximum Gamma-ray value (shale), respectively. Then, the shale volume can be calculated from the Gamma-ray index, by the unconsolidated younger rocks (Tertiary) formula [21]:

$$V_{sh} = 0.083\ [2^{(3.7 \times IGR)} - 1.0] \qquad (2)$$

Available core samples analyses show that the shaly material is dispersed throughout the sand and partially filling the intergranular interstices. The dispersed shale is in the form of accumulations adhering to or coating the sand grains, or it partially fill the smaller pore channels. Dispersed shale in the pores markedly reduces the permeability of the formation.

From SP

The SP method is the second most popular approach for determining the shale volume. The method works well in sands, but not in carbonates. The following equation is used to determine the shale volume [20]:

$$V_{sh} \leq 1 - PSP/SSP \qquad (3)$$

where: PSP is the pseudo-spontaneous potential of a thin shaly unit and SSP is the static spontaneous potential of a thick clean unit.

From Neutron porosity

The neutron log response in a formation is primarily a function of the formation hydrogen content. Since shale contains various amounts of water, the neutron porosity in a shaly interval is a function of both shale content and the liquid filled effective porosity. The volume of shale can be calculated from this equation [20]:

$$V_{sh} = (\Phi N_{log} - \Phi N_{min})/(\Phi N_{sh} - \Phi N_{min}) \quad (4)$$

where: ΦN_{log} is the neutron log reading for each studied zone, and ΦN_{sh} is the neutron log reading in front of a shale zone.

From Resistivity

It is noted that the most effect of shale in a formation is to reduce the resistivity contrast between oil or gas and water [30]. The volume of shale can be calculated using the following equation [31]:

$$V_{sh} = \left[\left[\frac{R_{sh}}{R_{t\log}} \right] * \left[\frac{R_{cl} - R_{t\log}}{R_{cl} - R_{sh}} \right] \right]^{1/B} \qquad (5)$$

where: R_{sh} is the resistivity log reading of a shale zone, R_{cl} is the resistivity log reading of a clay zone, R_t log is the resistivity log reading for each zone, and B is a constant, which equals 2 when $R_{sh}/R_t<0.5$ and equals 1 when $R_{sh}/R_t>0.5$. R_{sh} and R_{cl} are determined using GR and mud logs.

The usual approach for deciding which of the resulted shale volumes to use is to find the minimum or average value of the results. The minimum is chosen, because most of the errors for any method tend to increase the apparent shale volume. Then, the different zones were classified depending on the V_{sh} into clean (V_{sh} <10%), shaly (10 % <V_{sh}< 35%) and shale (V_{sh} > 35 %) zones.

2. Porosity Determination

Total Porosity (Φ_T)

In clean zone, total porosity can be read directly from neutron log (Φ_{CNL}) in limestone porosity units after making corrections for the borehole conditions. While, in shaly zones, the neutron log reading are given higher porosity than the actual effective porosity of the reservoir rocks, where shale have an appreciable hydrogen index. The neutron porosity can be corrected for the effect of the implied shales. The corrected porosity, as derived from the neutron log, can be thus manipulated according to the equation [32]:

$$\Phi N_C = \Phi N_{log} - V_{sh} * \Phi N_{sh} \qquad (6)$$

Where: ΦN_C is the neutron porosity corrected for shaliness effect ,
ΦN_{sh} is the neutron porosity of a shale zone, and
ΦN_{log} is the reading of neutron porosity from the log.

Effective Porosity (Φ_{eff})

This type of porosities depends largely on the degree of connection between the rock pores with each other forming channels, to facilitate the path of fluids through the lithologic contents. The effective porosity (Φ_{eff}) is calculated using the equation [20]:

$$\Phi_{eff} = \Phi_T * (1 - V_{sh}) \qquad (7)$$

3. Bulk Water Volume (BWV) Determination

$$BWV= \Phi_{eff} * S_w. \qquad (8)$$

Permeability Determination

Log-derived permeability formulas are only valid for estimating permeability in formations at irreducible water saturation (S_{wirr}) [33]. When a geologist evaluates a formation by using log-derived permeability formulas, the permeability values, if possible, should be compared with values of nearby producing wells from the same formation. Several formulas for calculating log-derived permeability by many authors exist (e.g. [34], [35], [36], [37], [38] and others). In an extensive statistical study [36] established a relationship between the formation resistivity factor (F) and permeability (K) in the form:

$$K=(7.0*10^8)/(F^{4.5}) \qquad (9)$$

Permeability is given in millidarcies. Also, permeability (in millidarcies) can be estimated using equation [38]:

$$K= (8400 (\Phi (S_{wir}+2)) / (1-\Phi)^2)/1000 \qquad (10)$$

The Permeability is defined as the volume of water of unit viscosity passing through a unit cross section of the material under unit pressure gradient in unit time. Permeability is measured of the ease with which water can flow through a formation.

The unit of permeability is the "Darcy ", one Darcy is that permeability which will allow the flow of one cubic centimeter per second of a fluid of one centipoise viscosity through a cross sectional area of one square centimeter under pressure gradient of one atmosphere per centimeter. Darcy is a very large unit so in practice, the millidarcy (md) is the unit commonly used which equal (0.001) Darcy.

Some rough relationships between effective porosity and permeability are existed, greater permeability in general corresponds to greater effective porosity, but this is far from being an absolute rule. Shale and some sand have high porosity, but the grains are so small that the path available for the movement of fluid are quite restricted and tortuous, thus, their permeability may be very low. So, capillary pressure data are required in such conditions.

Jorgensen [38, 39] reported on permeability estimating procedures that require data only on the cementation exponent (m) and effective porosity (Φeff).

Jorgensen equation for estimating permeability (K) in millidarcies is as follow:

$$K = 84000 (\Phi_{eff}{}^{m+2}) / (1 - \Phi_{eff})^2 \qquad (11)$$

Where: k is the permeability in millidarcy.

Φ_{eff} is the effective porosity (%). n is the cementation factor or exponent that equal 2.15 for sand.

5. Salinity Determination

The salinity is the amount of the total salts in water which is called the total dissolved solids (TDS). The ions contained in the solutions (mud and water formation) and their concentrations affect the short normal resistivity (LLS), and long normal resistivity (LLD) curves. In fact, resistivity is the reciprocal of conductivity, which is due to, the presence of ions of salt dissolved in the water filling the pore spaces of the rock. The larger the ionic content, the larger the conductivity and conversely, the smaller the resistivity.

Formation water resistivity (R_w) is obtained from SP log using the relation:

$$SP = - k \log (R_{mf} / R_w). \qquad (12)$$

R_{mf} is the temperature corrected mud filtrate resistivity at certain depth and k is a constant depends on temperature [26]. In special cases, the formation water resistivity may be determined using the ratio method [26]:

$$R_{xo}/R_t = (S_w/S_{xo})^2 . (R_{mf}/R_w) \qquad (13)$$

Against water zone, where S_w (uninvaded zone water saturation) = S_{xo} (flushed zone saturation) = 1, the value of R_{xo}/R_t is a maximum. Thus, the formation water resistivity can be obtained as:

$$R_w = R_{mf} . (R_t/R_{xo}) \qquad (14)$$

The average value, from the used methods, according to the available data, is taken in consideration.

Based on the calculated formation water resistivity, the salinity of the formation water (the total dissolved salts or TDS) in ppm was obtained from conductivity by using the following equations:

$$C = 10000/ R_w \qquad (15)$$

$$TDS = 0.64 * C \qquad (16)$$

Where: C is conductivity in micromhos/cm.

Another formula for estimating the salinity in ppm from the formation water resistivity directly [41] is:

$$TDS = K / R_w \qquad (17)$$

Where: K = 5300 for NaCl solution, 4200 for MgCl2 solution, 6700 for MgSo4 solution, 10.000 for Na HCO3 solution, and 12.000 for Ca (HCO3)2 solution.

Results, Discussion and Conclusions

VES Analysis

Geoelectrical cross-sections (Fig.7) deduced from depth, thickness and true resistivity of layers have been constructed for the Quaternary Aquifer (QA), which may demonstrate the aquifer geometrical and quality variation in Assiut Governorate.

Well Logging Analysis

(a) Qualitative interpretation

Logs were used for the identification of formation and water types, their lateral correlation, and the selection of likely producing intervals and confining beds for well completion. Clay layers are characterized by high gamma ray intensity and could be differentiated from sandy layers of low gamma ray values. SP log in normal cases can be used, as an alternative tool and/or for verifying such differentiation.

Twenty-one cross sections were suggested and constructed to cover the whole studied wells and the study area (Fig.8). The plotted gamma ray and resistivity data along cross sections were displayed and the detailed vertical zonation of the QA in each well from the ground surface to the end of the hole is represented, differentiated and correlated (Fig. 8).

(b) Vertical (level wise) presentation of the petrophysical parameters

The results of formation evaluation are illustrated vertically through litho-saturation crossplots representing the well logging deduced parameters downwards with depth. For the studied intervals in each well, the vertical distribution of petrophysical parameters and lithology, consists of a number of tracks display, from left to right, SP, GR, depth (in meter b.s.l.) and resistivity logs. At the right hand-side of the plot, lithology fractionation and fluid saturation are presented. This includes the porosity analysis (total and effective porosities), permeability index, and the lithofacies analysis (sand and shale), and the bulk water volume (BWV). The litho-saturation cross plots are constructed for QA in forty-four wells drilled in the study area (examples are shown in Figs.9 a, b, c).

(c) Horizontal distribution of the petrophysical parameters

The horizontal distribution of petrophysical parameters (porosity, permeability, clay content, gross sand, aquifer lithology and water quality) of QA in the investigated area are presented as contour maps (Figs. 10-17).

The investigation of these maps shows that the total porosity values (Fig. 10) vary in the range from 23.77% to 39.76%, the effective porosity (Fig. 11) from 21.16% to 38.46%, and the calculated permeability values (Fig. 12) reveal the high quality of the studied aquifer. Furthermore, the estimated low shale volume (4.48 to 25.88%) (Fig. 13) and high sand volume (45.59% to 65.62%) (Fig. 14) of the water-bearing horizon confirm also the good quality of the aquifer.

Total dissolved solids (TDS) calculated from well logging results (Fig. 15) are in the range from about 400 to 1000 ppm, which indicate fresh type of groundwater (Fig. 16 and 17).

The obtained parameters (Fig. 10-17) are useful in case of subjecting the area to hydrogeologic modeling or GIS studies for sustainable development of the Quaternary Aquifer in Assiut Governorate.

The present versatile study can be repeated and modified in case of the availability of much VES and well log data, and also can be applied in other areas where QA occurs, especially, in the Nile Valley of Egypt.

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الملخص العربي

عنوان البحث: التقييم التكوينى المتكامل لخزان المياه الجوفية الرباعي مبنيا على المقاومة النوعية السطحية وتحليل تسجيلات الآبار في محافظة أسيوط، وادي النيل، مصر

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مع الطلب المتزايد على المياه بسبب الزيادة السكانية والتوسع العمراني والزراعي في مصر، تكتسب موارد المياه الجوفية الكثير من الاهتمام. الهدف الأول من هذه الورقة هو تنفيذ وتفسير السبر الكهربائية العمودية (VES)في عدد من المحطات التي تغطي محافظة أسيوط لتحديد التكاوين تحت السطحية لرواسب الرباعي وكذلك لتقييم وتحديد التشكيل الهندسى للطبقة الحاملة للمياه الجوفية. الهدف الثاني هو استخدام تسجيلات الآبار بما في ذلك الجهد الذاتي(SP) ، و المقاومة الكهربية النوعية الضحلة و العميقة ، أشعة جاما الكلية (GR)، والنيوترون لتحديد خصائص المكمن تفصيلا من ٥٢ بئر محفورة وتقييم المعاملات الهيدروجيولوجية والبتروفيزيقية للطبقة الحاملة للمياه الجوفية.

تناول تفسير السبر الكهربائية العمودية تحديد عدد الطبقات الكهربية وسمكها ومقاومتها النوعية الحقيقية ، ورسم المقاطع العرضية الجيوكهربائية ، من بيانات العمق ، والسمك ، والمقاومة الحقيقية لتلك الطبقات ومن ثم تحديد الطبقة الحاملة للمياه. يعكس تفسير السبر الكهربائية العمودية الدور المتميز لتباين الخزان الرباعى في منطقة الدراسة للنمذجة المستقبلية.

تم تحليل تسجيلات الآبار على خمس مراحل تشمل الترقيم ، وجمع البيانات، والتصحيحات البيئية، التطبيع المتعدد وكذلك التقييم التكوينى باستخدام برنامج مصمم خصيصا لذلك.

وتناول تفسير سجلات الآبار تحديد الخصائص البتروفيزيائية لخزان المياه الجوفية الرباعي بما في ذلك معاملات المسامية الكلية والفعالة، والمحتوى الطفلى ، النفاذية، الصخرية، ملوحة المياه والعطاء الكلى ، والتي تم عرضها في قطاعات صخرية-تشبعية وعبر خرائط توزيع كنتورية.

كشفت الدراسة عن خصائص تشير إلى أن الطبقة الحاويه للمياه الجوفية التابعة للرباعي لها قيم عالية من المسامية والنفاذية ومنخفضة إلى معتدلة فى المحتوى الطفالى وفى نسبة الأملاح الذائبة بالمياه (TDS) والتي بدورها تشير الى وصف الخزان بأنه ذات جودة عالية.