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Formation Evaluation of Bahariya Groundwater Aquifer Using Nuclear Logs in the Southwest area of Bani Sweif, Upper Egypt, (A Case Study)

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***ABSTRACT*:Over the last decade, rapid development has occurred in Upper Egypt's western desert regions to address water shortages in irrigation and domestics. The national state plan seeks to reclaim one and a half million acres of these areas. Because of the increasing demand for water, it is important to identify aquifer characterization in terms of petrophysical properties which are obtained from geophysical well logging analysis. The nuclear well logs are used in this study to estimate the physical properties and evaluate the Bahariya formation, which is subdivided into Upper and Lower Bahariya formation. Theses logs are (RHOB), neutron (APLC), gamma ray (GR) besides resistivity (AT60-AT30-AT90), caliper (CAL), and sonic (DT) record logs to give more information about aquifer characterization. The results clarify that the Lower Bahariya formation is mainly composed of fine to medium-grained sandstone and clay, which may indicate low permeability where, The Upper Bahariya is exhibited poor sand succession. The hydraulic conductivity of the studied aquifer has a minimum value of 1335.97 mdarcy at well WBS1. It increases in the south direction and decreases in the other direction of the area under investigation. Shale volume (V_{sh}) reaches the maximum percentage of 31.7% at WBS1 well and the minimum percentage is 14.7% at WBS2. In addition to the porosity and permeability can reveal the quality of the studied aquifer, which decreases in the west-south direction and increases in the south and southeast parts of the study area. This study can help in making decisions to save and protect groundwater resources in the future.**

Key wards: Neutron; Gamma Ray; geophysical well logging; Bahariya Formation, Upper Egypt.

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1. INTRODUCTION

The groundwater aquifer is considered the most renewable natural source for sustainable development in the world (Das et.al., 2018). This is related to pollution, which may have an effect on the nature of surface water on a large scale. Nowadays, it is very important to study the aquifer characterization to help in reserving the quantity of water for the future. Because of the increasing demand for water, it is important to identify aquifer physical properties. This is obtained from using geophysical well logging as it helps in delineating aquifer characteristics under hydrogeological conditions of the investigated sites (Akpan et al. 2015).

Aquifer evaluation is the most vital tool for detecting subsurface physical properties, so it's possible to maximize field exploitation, such as conducted by Abdel-Fattah, and Alrefaee, (2014); Abdel-Fattah et al., 2010;2015). Consequently, evaluation of deep groundwater aquifers relates to the determination of aquifer properties such as porosity (Φ), effective porosity (Φeff), hydrolytic conductivity, permeability (K), and shale volume (V_{sh}). The primary goal of this research is clarifying and evaluating deep groundwater aquifers and their characterizations through the use of Nuclear well logs such as Gamma ray, density and neutron logs. The study area is located in the western desert fringes of Upper Egypt Governorates, between longitudes 29°05 and 30° 39` E, and latitudes 27° 23` and 28° 58` N (Fig. 1). Bani Sweif area is characterized by an arid to semi-arid climate with a hot, dry summer climate and mild winters with little rainfall. The average rainfall over the last 15 years (2000–2016) has ranged from 23.05 to 33.15 mm/year. It has a high evapotranspiration rate of 4897.91 mm/year. Average temperatures In January, temperatures range from 4.5 ˚C to 20.5 ˚C, while in August, temperatures range from 20.5 ˚C to 37.7 ˚C. The relative humidity varies from 68% in January to over 70% in June.

Questions have been raised about the safety of groundwater aquifers for future use. The following are the main topics that this research discusses: (1): How to use a geophysical well logging tool to assess the petrophysical properties and water potential of the Bahariya Formation (Nubian sandstone aquifer) in southwest Bani Sweif are, Western Desert. (2) What the effect of the Neutron log fingerprint on aquifer characteristics, particularly porosity (%). Abu Seda (2010) investigated the effect of lithological anisotropy of the Bahariya formation in the Khalda concession, whereas Halish et al. (2009) investigated the petrophysical properties of lower part of t Bahariya formation, which included rock density, permeability, complex resistivity, p-wave velocity, and so on. A number of researchers have reported that the Bahariya Formation is divided into upper and lower units (Watkins et al., 2002; Wehr et al., 2002; and Metwalli et al., 2000). Wehr et al. (2002) pointed out that the Lower Bahariya formation is mainly composed of fine-to medium-grained sandstone and clay, which may indicate that it formed in a shallow marine environment. On the other hand, Upper Bahariya was recorded as sand poor succession deposited in a condition of low-energy, restricted marine (Wehr et al., 2002).

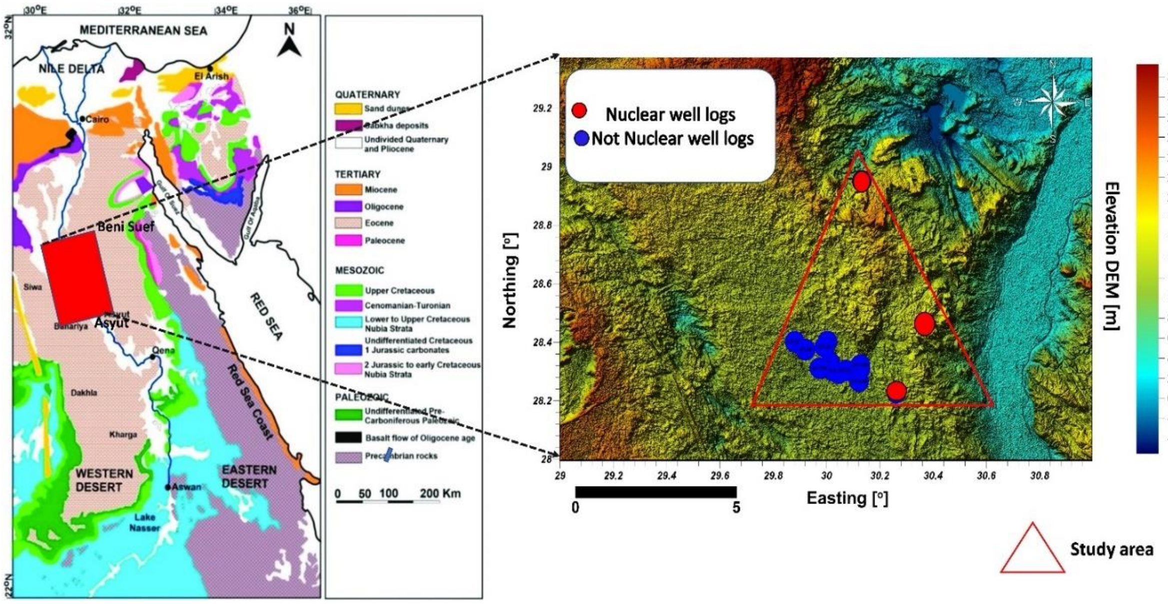

Fig. (1): location map of the investigated area with the three oil well locations (red circle) of nuclear records.

1.1 Geomorphology and Geological setting

The study area is divided into four geomorphological units, according to Salem (2015) and Shabana (2010), including tableland, floodplain (gravely, silt, and sandy plain), isolated hills, and sand dunes belt. Fig. (2).

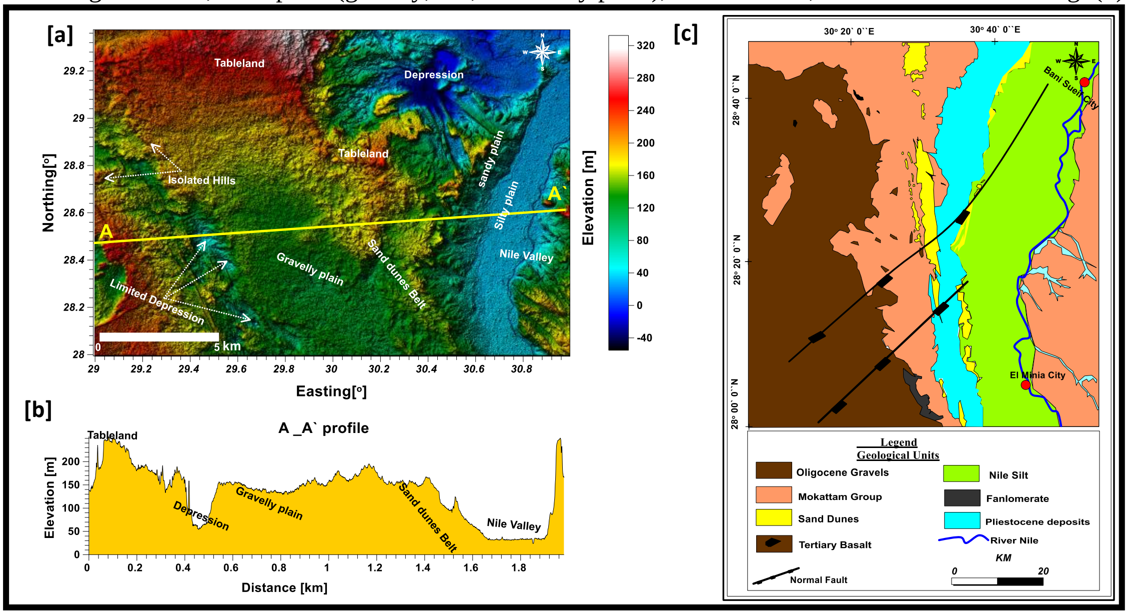

Fig. (2): (a) Geomorphology map of study area, (b) Geomorphic unit crossing study area along A-A` profile, (c) Geological unit of study area (after Shabana, 2010)

The geological setting of the Western Desert has been discussed by many authors, such as Yousif et.al., (2018), Abdel Baki (2013), El Kashouty et al (2010), Abou Heleika and Niesner (2009), Abd El-Aziz (1994) and Said (1981). The groundwater was extracted from the fractured limestone and Nubian sandstone aquifer. According to Shabana (2010) there are more than one waterbearing formation were identified in the study area, including Oligocene aquifer, Middle Eocene limestone aquifer and Nubian sandstone aquifer. A network of faulting systems affects the research field. The occurrences of groundwater aquifers in this region are strongly affected by these faults; El Kashouty et al., (2010); Abou Heleika and Niesner (2009), Fitzner et al., (2002); and Said (1981). The aquifer is composed of Paleozoic-Mesozoic sandstone embedded with shale and clay beds and overlaying impermeable crystalline basement rocks. The thickness of the aquifer varies up to 3500 m (Shata, 1982, Mohamed et.al., 2017). In the Western Desert, the aquifer is unconfined south of latitude 25° N where the sandstone outcrops and confined to the north where the sandstone is overlain by impermeable marine shale and clay (El-Rawy et. al., 2020). The age of the groundwater is estimated between 20,000 and 49,000 years. Estimates of water storage in the Nubian sandstone aquifer in Egypt are around $40{,}000 \times 10^9$ m^3, but this is non-renewable because groundwater recharge in the Western Desert is negligible (El-Rawy et. al., 2020). The large-scale development of the Nubian sandstone aquifer in Egypt started in 1960 in the major oases of the Western Desert and the total extraction of groundwater is expected to be in the order of 2.8 10^9 m^3/y for the year 2020 (CEDARE,2014)

Figure (3) represents the lithostratigraphic column for the Western Desert, where the study area southwest of Beni Sweif is located. Pre-Cambrian basement, Cretaceous sequence, which occupies the majority of the stratigraphic succession over the study area, and until the Apollonia formation of the Eocene age, which is composed primarily of carbonate rocks, followed by Oligocene shales of the El Dabaa formation (Makky et al.,.2014). According to Hantar and Balkema (1990), the cretaceous sequences are divided into two units (lower and upper units). The lower unit is mainly composed of clastics and is subdivided into five units from base; these are the Betty, Alam El-Buieb, Alamein, Dahab, and Kharita formations. On the other hand, the upper unit is completely formed of carbonates. The upper unit of the Cretaceous is subdivided into three units from base to top: Bahariya (Nubian sandstone) of two units (upper and lower Bahariya), Abu Roash of seven members (A to G). Members A, C, E and G are formed from fine clastic with intercalation of carbonate, whereas members B, D and F are composed of 100% carbonates and the Khoman formation, which is mainly composed of chalky limestone (open marine deposits of outer shelf condition).

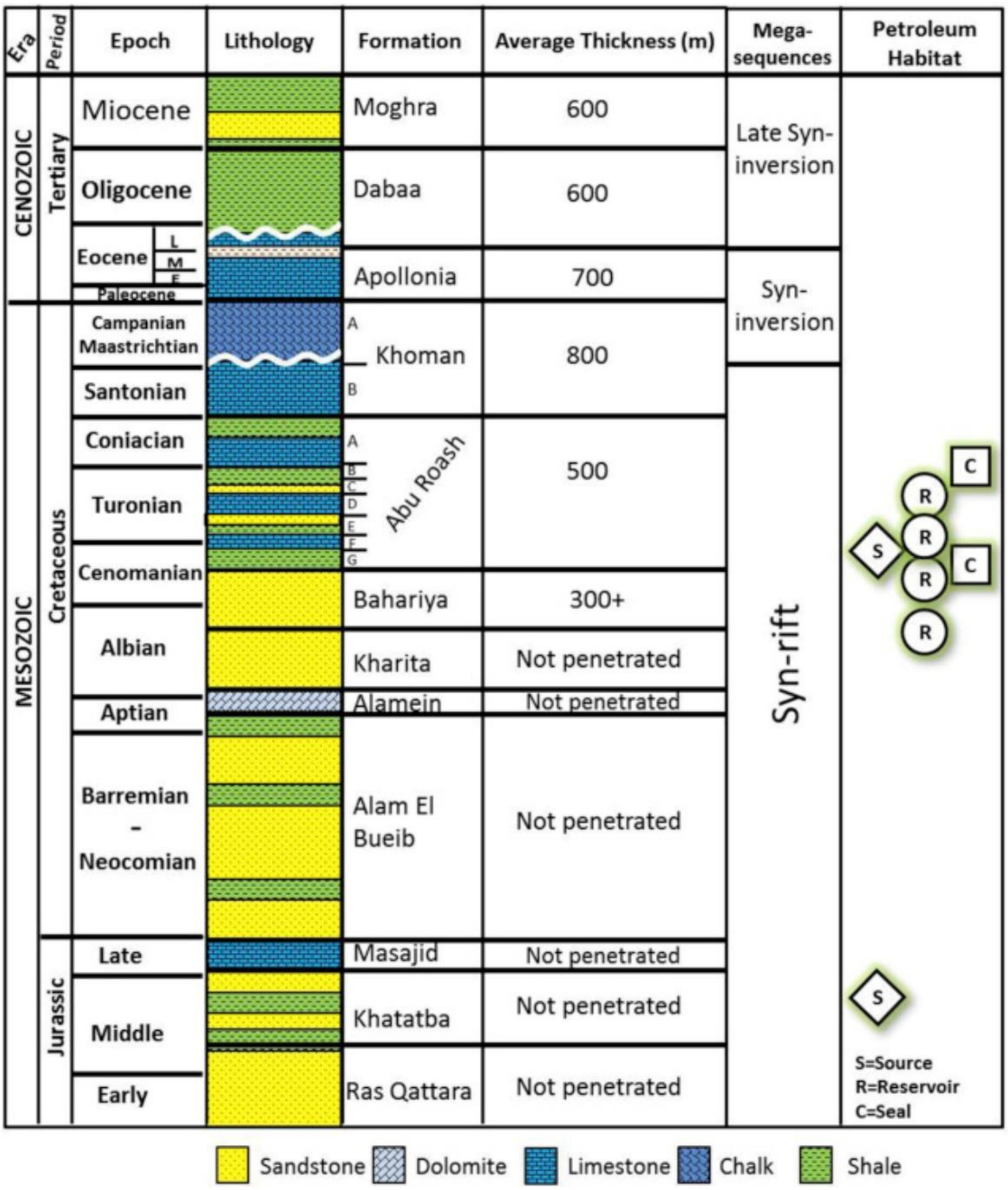

Fig (3): Generalized litho-stratigraphic column for Western Desert, Egypt (Schlumberger 1995)

2. MATERILS and METHODS

For several generations, the nuclear technique has been an essential well logging method that employs four (4) common techniques to examine an aquifer's geological formation (Bala et al., 2022):

1. Natural Gamma ray tool: This equipment comprises of one or more gamma ray detectors that are not powered by a radioactive source. It detects Gamma rays released by naturally occurring radioactive sources (NORM) in minerals such as the Uranium and Thorium decay chains, as well as 40K decay. This is usually used to determine the kind of rock.

2. Gamma-Gamma ray tool:A gamma ray source (typically 137Cs) and one or more gamma ray detectors comprise this tool (commonly used is NaI:Tl). It calculates the density of materials surrounding the well probe using Compton-scattered photons from the gamma ray source.

3. Neutron porosity tool: This tool comprises of a fast neutron source (AmBe, AmPu, or D-T) and one or more neutron detectors (often 3He) to determine the porosity of rock formations (fluid content).

4. Neutron-gamma density tool: A neutron source and one or more gamma ray detectors comprise this tool. It makes use of the neutron-gamma generation process. The available well data is depicted in table (1). Three oil well logs: WBS-1, WBS-2, and WBS-3 (Fig. 4) are used to delineate aquifer characteristics in the study area. The

available geophysical well logs for West Bani Sweif oil wells are density, neutron, gamma ray, resistivity, caliper, and sonic logs.

Table (1): Available geophysical well logging data for the study area.

No.	Name	Available data
1	WBS- 1	
2	WBS- 2	
3	WBS- 3	Density (RHOB), neutron (APLC), gamma ray (GR), resistivity (AT60-AT30-AT90), caliper (CAL), sonic (DT) logs

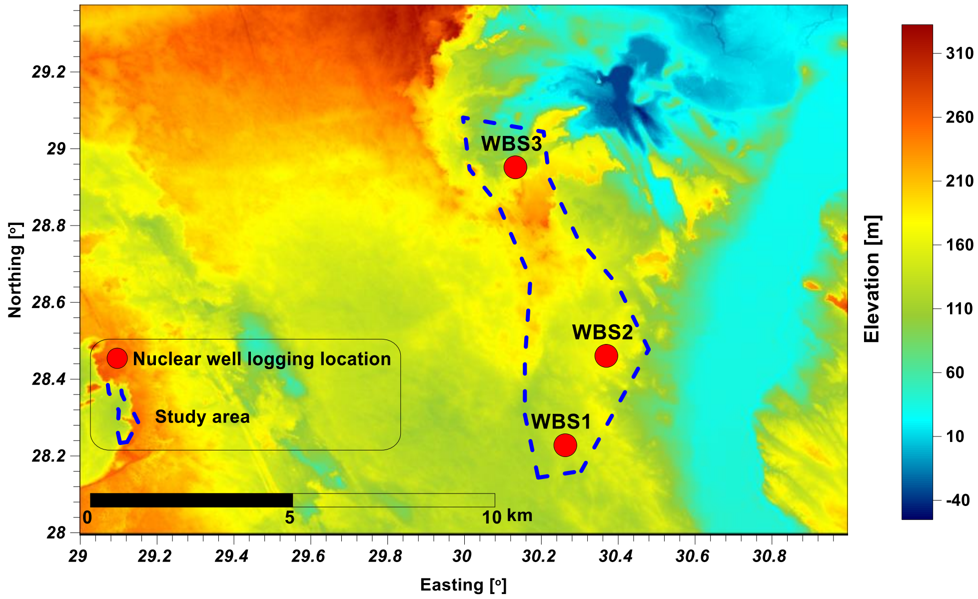

Fig. (4) Available three oil wells with nuclear records

2.1 Nuclear logging

The main nuclear tools are the Gamma-Gamma Density (Gamma-Gamma) (LSD) and Neutron Log (NEUT). These tools were used as porosity logs for all types of wells. The gamma ray tool depends mainly on a radioactive source of Cs-137 with 3.7 GBq, which emits 662 keV gamma ray photons into the formations. The energy of gamma rays that reach the formation interacts mostly by Compton scattering. This radiation interaction with the matter is dependent only upon the number density of the scattering electrons. This in turn is directly proportional to the bulk density of the formation.

2.1.1Gamma log

This tool measures the formation's natural gamma radiation (natural radioactivity, K-40, U-238, and Th-232). The uranium-radium series has a half-life time of 4.4*109 years, whereas the thorium series and potassium K40 have half-live times of 1.4*109 and 1.3*109 years, respectively (from Heriot-Watt University, 2018).

2.1.2 Gamma- Gamma (Density) logs

In terms of gamma radiation produced by a source (as part of the instrument) with the formation is used in gamma-Gemma techniques. In terms of gamma material interaction, three effects exist: photoelectric effect, Compton effect, and pair production. The probability of interaction is determined by the gamma radiation's energy and the target material's atomic number.

2.2 Neutron logs

The neutron log principle is based on the dominant effect of hydrogen as a component of porous fluids, which is used to determine neutron porosity via elastic scattering. The observed neutron porosity is exactly the true porosity because the neutron instrument is calibrated for a limestone matrix with fresh water as the pore fluid. The interaction of neutron radiation from a source (as part of the tool) and the formation is used in neutron techniques. Fast neutrons are classified according to their energy as Fast neutrons > 500 keV, Intermediate neutrons 1 to 500 keV, and Slow neutrons <1 keV (epithermal 0.1 to 1 keV, thermal < 0.1 keV). A neutron reacts with the nuclei of the target material as a particle radiation (a neutron has about the same mass as a proton). Different sorts of interactions exist as moderating interactions. Energy is reduced due to (slowing down effect of inelastic scattering and elastic scattering. Another one is capturing interactions. For a different formation or pore fluid, corrections are necessary, such as for sandstone or dolomite, which have a different neutron effect than limestone; a shale correction is necessary due to shale's high amount of H and this result in high neutron porosity, so the neutron log can be used as a shale indicator. Asquith et al (2004), Brown (1967). and Connolly (1965) clarify that geophysical well logs (Oil /Water) are critical for determining the physical parameters of viable zones as evaluate aquifer characteristic.

The lithology is estimated from cross plots methods, the neutron-density, neutron-sonic, and M-N cross-plots.

Shale volume (V_{sh}) is estimated from GR log by using equation:

$V_{sh} = 0.5 * IGR/(1.5 - IGR)$ (Fertl and Frost 1980) [1]

$IGR = \frac{GRlog - GRmin}{GRmax - GRmin}$ (Schlumberger 1974) [2]

Where (I_{GR}) is gamma ray index, $GRlog$ is the gamma ray log reading at any depth, $GRmin$ is the minimum gamma ray reading and $GRmax$ is the maximum gamma ray reading

Shale radioactivity is typically higher than that of sand or carbonate, and it is used to determine the percentages of shale in each aquifer zone. The GR logs could also discriminate between clean and non-clean aquifers using shale base lines and identify the zone of water bearing. In these cases, the V_{sh} values in the water-bearing zones for three wells range from 14.7 % in the WBS-2 well to 32.033 % in the WBS-3 well. (Schlumberger1972).

Porosity (Φ): The percentage of a rock's total volume that is devoid of solid constituents is known as porosity. It can be calculated from neutron or density logs for the oil logs where Φ equal to neutron log reading or from density logs(ΦDen) by using the following equation:

$\Phi = \frac{\rho ma - \rho b}{\rho ma - \rho f}$ (Asquith and Gibson 1982) [3]

Where ρma is matrix density, ρb is (bulk density) density log value,

(ρf) is fluid density=1 g/cm^3

To calculate effective porosity (Φ_{eff}) we use the following equation:

$\Phi_{eff} = \Phi*(1 - V_{sh})$ [4]

The hydraulic conductivity (K) calculates from effective porosity by using equation

$\Phi_{eff} = 0.462 + 0.045 \ln K$ (Martoz,1968) [5]

The permeability (K) calculates from porosity from formula:

$K^{1/2} = 100 * \Phi^{2.25} / s_{wirr} * 1000$ (Timur1968,ptman,1992) [6]

Where s_{wirr} is irreducible water saturation=5.2297 Φ

For water study the water saturation (R_w) equal 1.

3. RESULTS and DISCUSSION

3.1 Formation Evaluation

For formation evaluation of the studied wells, two connected practises are discussed. Firstly, qualitative (Quick Look) interpretation for a permeability examination of the logs and identification of the interesting zone (Fig.5), and secondly, quantitative interpretation to determine lithology, shale content, porosity and mineral composition, and fluid saturation. In general, the goal of interpretation is to determine the lithological profile identification and characterization of prospective aquifer zones by using cross-plot methods. Shale type (laminated, dispersed) and shale content, Porosity, Permeability can estimate in this study by employs IP (Interactive Petrophysics) software.

3.2 Lithology Determination

The study area is divided into four units: the Apollonia formation, the Khoman formation, the Abo Roash formation, and the Bahariya formation. In this study, we deal with the Bahariya formation, which is represented in the three wells. The Bahariya (Nubian sandstone) aquifer has a low gamma ray reading unit. According to the gamma ray log, a slight deflection within the Nubian sandstone unit, intercalated shaly partings are exposed. The Bahariya (Nubian sandstone) aquifer is divided into two subunits: lower and upper Bahariya.

3.3 Cross-Plot's methods

Gamma ray (GR), neutron (APLC), sonic (DT), and density (RHOB) readings are used as indicators to identify the lithology and detect the interesting zone over the study area. Well logs can be detected in the Bahariya formation and their lithology can be identified using lithology analysis cross plots. Density-neutron, neutron-sonic, and MN cross-plots are used to determine lithology. For example, the three oil logs in this study area are used to identify the lithology of the Bahariya formation (Lower and Upper) using cross-plot methods.

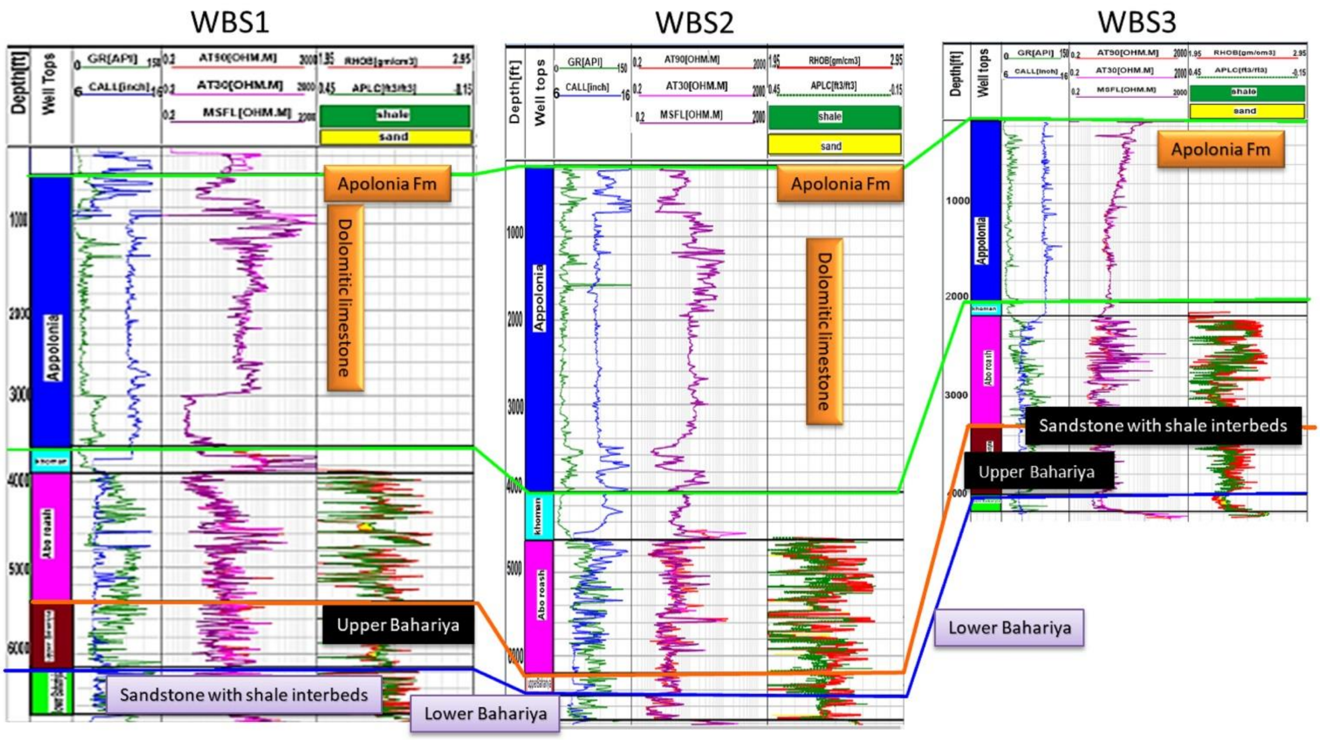

Fig. (5) Correlations among the trending well log of the three West Bani Sweif wells (WBS) to evaluate Lower and Upper Bahariya formation**.**

3.4 Neutron–density cross plots

Shale type cross-plots

Neutron–density cross plots are widely used to determine lithology and effectively estimate the matrix porosity of calcareous rocks. On this cross plot, the effect of light hydrocarbons (gas) can be seen as the plotted data migrates northwesterly from the limestone line. This effect is observed by a decrease in phi neutron(ΦN) and an increase in phi density(ΦD). Also, the effect of shale can be obtained from this plot where the plotted data migrates towards the southeast cross plot (Poupon and Leveaux, 1971). In this cross plot we used phi density(ΦD) and phi neutron (ΦN) to demonstrate the lithology and shale effect.

For the upper Bahariya formation, the maximum phi density (ΦD) is 0.4542 at well WBS 1(Fig6.a) and the minimum is 0.003846 at well WBS3 (Fig6.c). Also, for the upper Bahariya formation, the maximum phi neutron (ΦN) is 0.451 at well WBS1(Fig5.a). The lowest one is 0.093 at well WBS 2 (Fig.6.b). It means that the shale effect in well WBS3 is greater than in WBS1 and WBS2. Due to the migration of plotted data towards the southwest of the cross plot, for the lower Bahariya formation, the maximum phi density is 0.44774 at well WBS 1 (Fig6.a). The lowest value is 0.000645 at well WBS 2 (Fig.6.b). Also, for the lower Bahariya formation, the maximum phi neutron is 0.4471 at well WBS 1 (Fig6.a), and the minimum one is 0.067 at well WBS 2 (Fig6.b). It demonstrated that well WBS 2 is more affected by shale than the others (WBS1 and WBS3).

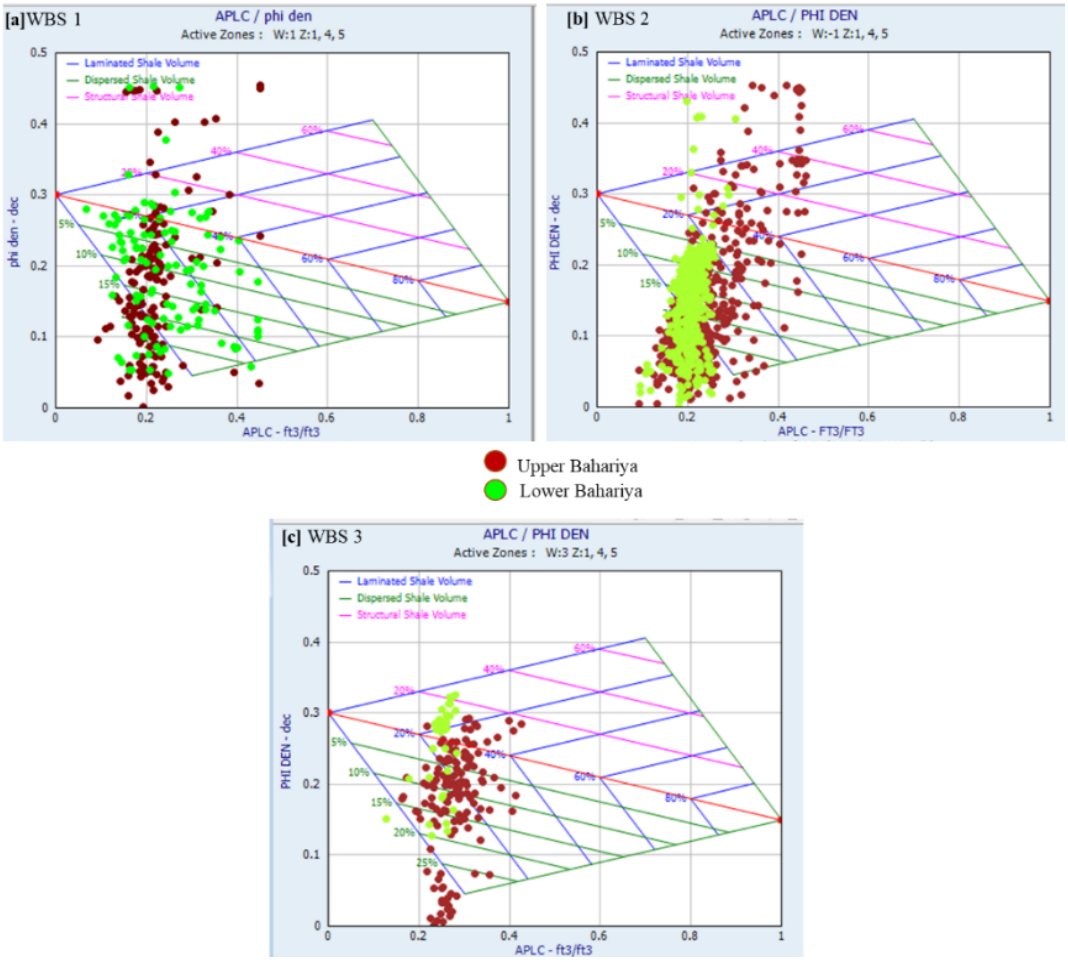

Fig (6): Shale type cross plot at three logs for upper and lower Bahariya formation; [a]for WBS 1, [b]; for WBS 2 and [c]; for WBS 3.

3.5 GR- phi neutron cross plot

In this cross plot (Fig.7), gamma ray (GR) and phi neutron (APLC) are used. The scattering of plotted data indicates lithology differences in this rock unit. It demonstrates that low GR and low phi neutron (APLC) points indicate the existence of limestone and dolomite, medium GR and medium APLC points suggest sandstone, while high GR and high APLC points indicate the presence of shale. It is obvious from the comparison that the dominant lithology is sandstone mixed with limestone and a small amount of shale. It is apparent from these plots that WBS1 at Figure (7a) that GR and APLC are moderate for the upper and lower Bahariya formations, which means that the lithology of this formation is mainly sandstone.

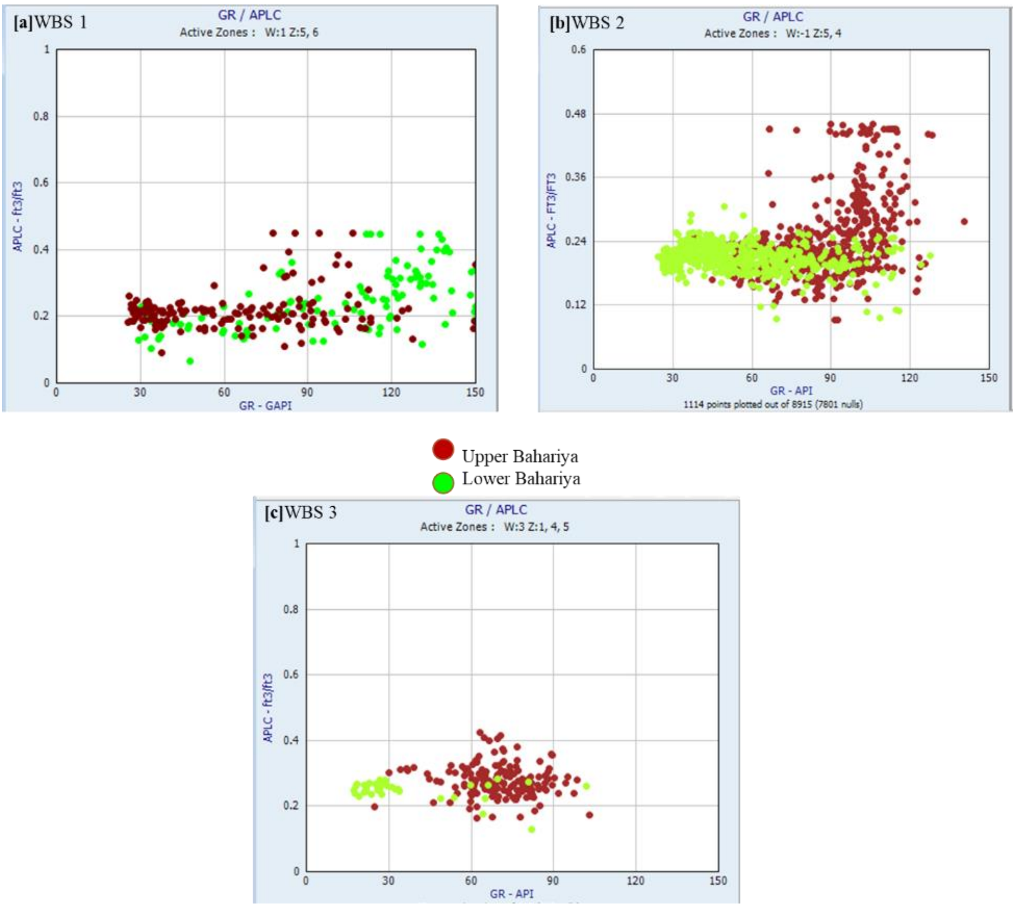

Fig. (7): GR-phi neutron cross plot at logs [a]; WBS 1 [b]; WBS 2 and [c]; WBS 3.

GR-RHOB Cross Plot Identification

In this plot we used gamma ray (GR) and density logs (RHOB). Figure (8) depicts the same information as the previous one, but the density of limestone and dolomite is higher than that of sandstone. As a result, the points of limestone and dolomite are plotted in the cross plot in the left direction. Therefore, it may be deduced that the main lithology of this aquifer is sandstone with shale and carbonate, based on the cross-plots. As can be seen from the highest-plotted places along the sandstone line in those cross plots, the sandstone content is often high.

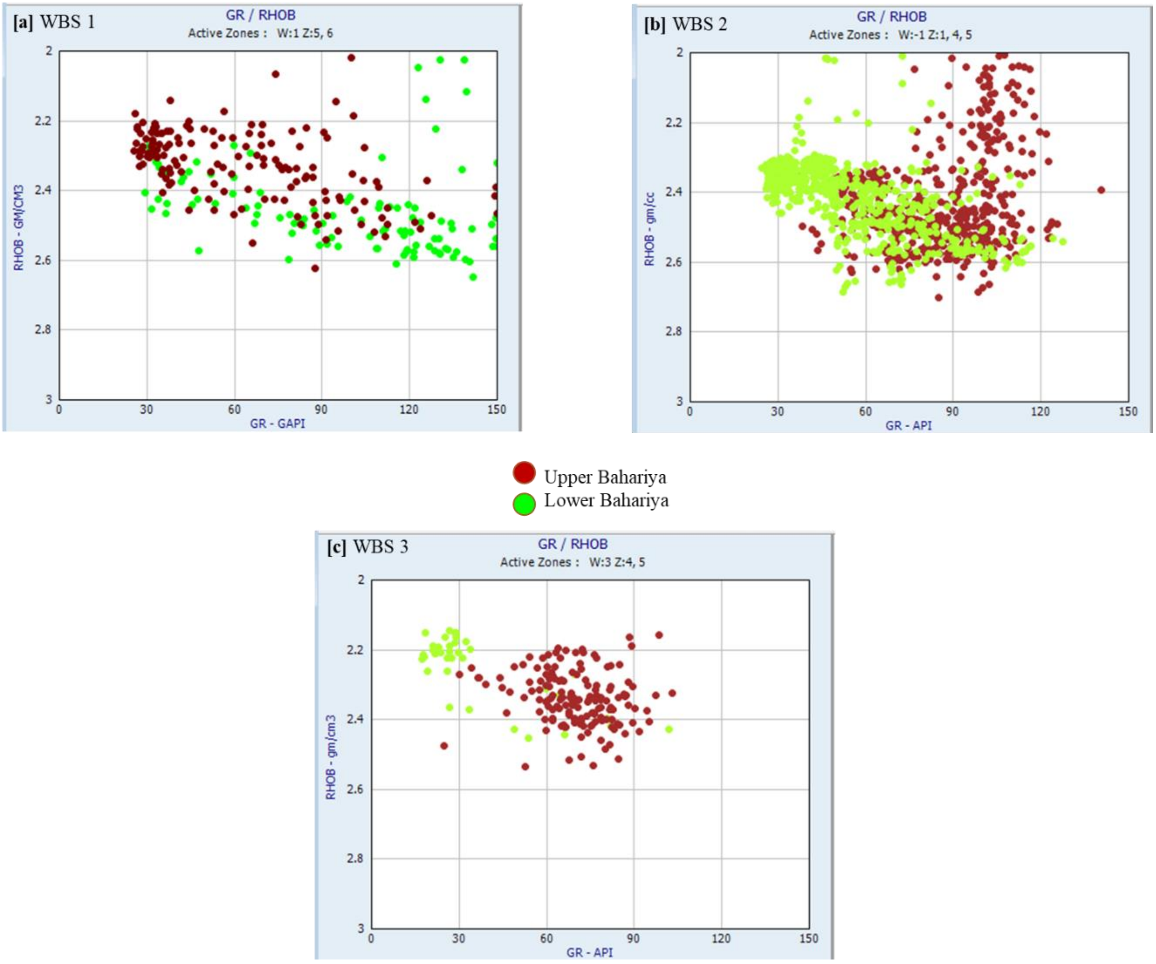

Fig. (8): GR-RHOB cross plot at logs [a]; WBS 1 [b]; WBS 2 and [c]; WBS 3.

Porosity-Lithology cross plot

Figure (9) shows neutron (APLC) and density (RHOB) cross plots of the upper and lower Bahariya formation for WBS 1, WBS 2 and WBS 3. This cross plot (Fig. 9a) of well WBS1 indicates that the plotted data is scattered in between sandstone and limestone with porosity ranging from 9.3 to 46.1%. Owing to the effects of shale, the majority of points are dispersed downward through the dolomite line. This means that shale lithology is present, along with sandstone and limestone streaks. A neutron–density cross plot of the lower Bahariya aquifer found that data is scattered in between the sandstone line and limestone with porosity ranging from 6.7 to 44.7%. also Owing to the effects of shale, the majority of points are dispersed downward through the dolomite line.

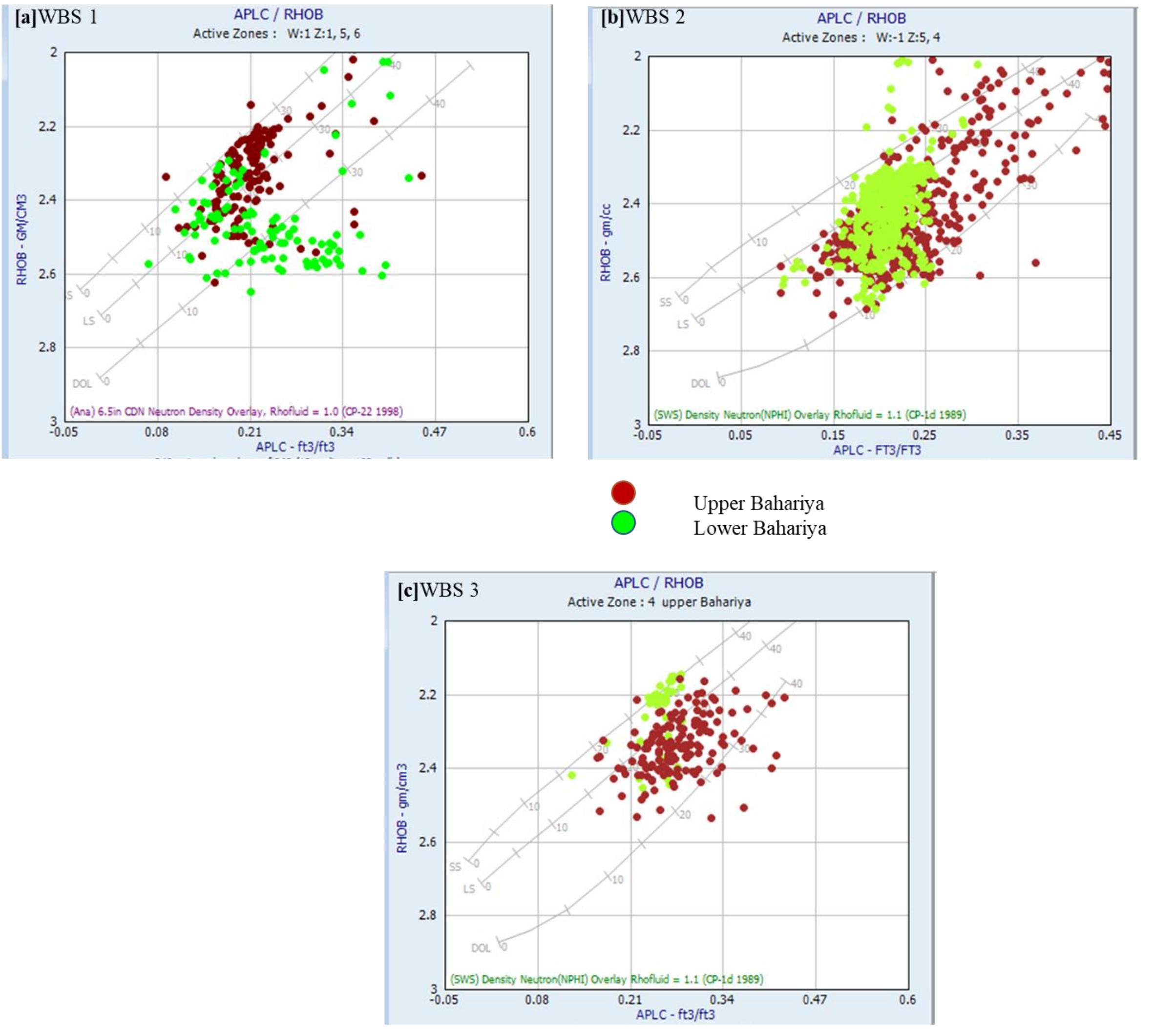

Fig (9). APLC/RHOB, Lithological identification Cross-plots of Bahariya formation for three logs[a]; WBS 1 [b]; WBS 2 and [c]; WBS 3.

Figure (10b) shows the distribution of the upper and lower Bahariya formation at wells (WBS1, WBS2 and WBS3). From this data, we can see that the resultant percentage of Upper Bahariya reaches its maximum value (31.5%) at well WBS1 and the lowest percentage at well WBS2 is around 14.7%. Otherwise, the percentage of lower Bahariya at the three oil wells is so close. The maximum one is 31% at WBS 1, 26% at WBS2 and then 22% at WBS 3.

Table 2: summarized the finding of Bahariya formation evaluation via three oil wells of west Bani Sweif.

Well	Aquifer	Coordinate N	Coordinate E	Total thickness(m)	Total depth m	Depth to water(m)	Porosity Φ (%)	Effective porosity Φeff (%)	permeability (k) in mdarcy	hydraulic conductivity (k) in mdarcy	V_{sh}(%)
WBS1	UPPER BAHARIYA	30.2623	28.2279	99.3648	2072.64	1644.0912	21.721	14.9232	1695.4956	1348.8905	31.5812
WBS2		30.3690	28.4607	82.6008	2103.12	1892.5032	17.903601	17.7547	3087.6849	1523.8235	14.7649
WBS3		30.1324	28.9517	214.2744	1310.64	1009.1928	27.9716	18.1721	1878.5813	1345.0364	31.0552
WBS1	LOWER BAHARIYA	30.2623	28.2279	302.3616	2072.64	1743.456	24.536	13.2508	1585.3528	1310.1223	32.0335
WBS2		30.3690	28.4607	86.8395	2103.12	1975.104	19.39167	17.5610	1964.3312	1440.1947	26.0592
WBS3		30.1324	28.9517	53.0352	1310.64	1223.4672	24.7386	18.0292	1750.9523	1460.8821	22.9095

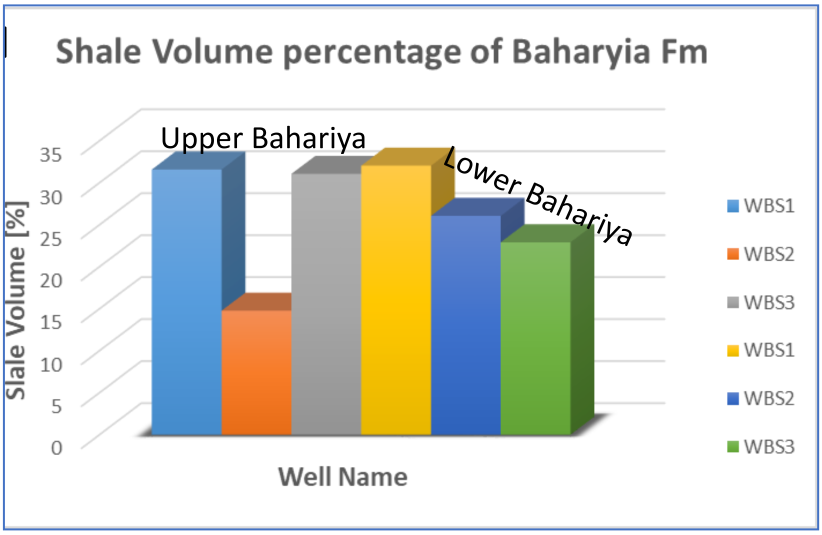

Figure 10. Clustered column for the percentage of shale volume of upper and lower Bahariya Fm for wells

To sum up, the results of geophysical well logging analysis are presented in porosity, effective porosity, permeability, and shale volume. Results show a strong relationship between GR and phi density and phi neutron in the literature to identify the lithological formation and effect of shale. It shows that porosity is generally high with very good connectivity (high permeability) in which the majority of pore spaces are megaspores, particularly for the Bahariya formation (Lower and Upper units). The results also show that the quality of Bahariya formation is still good where values of permeability are higher than 1000 md as mentioned in Abuzaied et al., (2020). The quality of the studied formation as detected by porosity is good, with porosity ranges between 18% and 28% for Upper Bahariya and Lower Bahariya, which is slightly less than the upper one.

4. CONCLUSION

Geophysical Nuclear well logging analysis using cross plots methods or Archi equation is successful in the description of the hydrogeological environment of aquifer systems in the study area and evaluates the aquifer characterization for developing water resources. Nuclear Well-log analysis in the hydrogeologic evaluation of oil wells in the Bahariya formation southwest of Bani Sweif area yields information on both the physical properties of the aquifer and the depth to the top of the groundwater bearing layer. Gamma-Gamma (Density) logs are considered a porosity and shale volume calculation tool. On the other hand, neutron log directly provides the true porosity. Moreover, it can easily differentiate between sandstone, dolomite, and limestone. Besides, it estimates shale content as well as shale type. Neutron–neutron and caliper measurements could estimate the physical properties of Bahariya formation and identify the lithology of each formation unit. However, the present study hasn't collected core samples for analysis and determination of the petrophysical parameters. The nuclear well logs are successed in achieving the aim of study and assessing the aquifer and classifying it as clean or not. Here, in this study the results found that percentage of V_{sh} and the percentage of porosity and permeability parameters can reveal the quality of the aquifer. The study recommended to tack the southwestern parts of the study area into account in the future sustainable development where V_{sh}percentage is decreases and porosity and permeability increases. It is highly recommended that [1]; aquifer quality mainly depends on the percentage of pores (porosity), permeability, and shale volume. [2]; as shown in that study, increasing porosity and permeability improves aquifer quality; [3]; these parameters can aid in making decisions to save and protect groundwater resources.

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