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Geohydrodynamic properties of hydrogeological units in parts of Niger Delta, southern Nigeria

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ABSTRACT

We used geophysical and laboratory techniques to study the geohydraulic properties of the geological units in the Niger Delta of southern Nigeria. Our main objective was to investigate the distribution of the geohydrodynamic parameters and to establish the interrelationships among them in the study area for effective characterisation of hydrogeological units. Measurements on the core samples aided in the estimation of effective porosities. The hydrogeological units' bulk resistivities measured from 1-D resistivity data constrained by nearby boreholes and the formation pore-water resistivities measured in the laboratory were used in computing the hydrogeological unit formation factor resistivity. Integration of field and laboratory measurements in conjunction with regression analysis of the data led to the determination of the hydrodynamic coefficients of the hydrogeological units. The graphs and the contour maps generated from the data show the variations and the interrelationships among the parameters. A theoretical model for the porosity–resistivity formation factor relation which conforms to Dakhnov's formulation, obtained for similar sediment with different grain sizes in another geological province has been developed based on the measured data. A good approximation with error of the mean square of 2.48 and standard deviation of 1.5 was obtained between the experimental aquifer formation factor F and the predicted aquifer formation factor F_m. Generally, the results of our study reveal good correlations with similar studies carried out in literatures at different places. The juxtaposition of contour maps which show variations of geohydraulic parameters in a continuum is worthwhile. The changes in geohydraulic parameters are influenced by size of grains, magnitude of pore sizes and shapes, pore-water and formation conductivities, facies changes and anisotropy of aquifer sediments. Our results have not really shown any interaction between freshwater and saltwater within the potential aquifers despite the proximity of the salt water within the area.

1. Introduction

Presently, the rising quest for dependable and potable groundwater resources has gained relevance in the study of groundwater (George et al., 2013, 2014). Consequently, the quantitative description of aquifer repositories is paramount in searching for solution to hydrogeological and hydrological problems (Martínez et al., 2008). This, therefore, provoked the study of geohydraulic parameters, which would be useful in contaminant migration modelling and improvement of the quality of model in the study area. The integration of field and laboratory methods can be useful in estimating the various hydrogeological parameters that can be useful in modelling of the hydrogeodynamic potential of an area. Geohydraulic properties are very useful in quantifying the subsurface hydrogeological units such as aquifers or oil reservoirs (Akpan et al., 2013, 2015; Ebong et al., 2014) and exert a tremendous influence on fluid flow in the subsurface formations. The effective porosity is central in fluid flow. It gives information about the communicating pores or dead – end pores and the pore dynamics (Obinawu et al., 2011). Adequate understanding of the pore properties and their interrelations could provide information on flow modelling and hydrogeological unit pore pressure prediction which is a useful guide in choosing a matching pump for borehole supply. The determining coefficient of effective porosity known as formation resistivity factor F is given in expression below;

$$F = \frac{\rho_b}{\rho_w} \tag{1}$$

where ρ_b and ρ_w represent the bulk resistivity and the water resistivity respectively.

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Specifically, for sedimentary formations, Archie (1942) and Winsauer et al. (1952) proposed a diagnostic equation regarded as Archie–Winsauer equation. The equation shows the dependence of resistivity formation factor F on fractional porosity, ϕ in relation to the dimensionless pore geometry factor a and cementation factor m;

$$F = \frac{\rho_b}{\rho_w} = \frac{a}{\phi^m} \quad (2)$$

Taking the natural log of $F = \frac{a}{\phi^m}$ in Eq. (2) gives the expression in Eq. (3).

$$\log a = \log F + m \log \phi \quad \text{or} \quad m = -\left\{\frac{\log F - \log a}{\log \phi}\right\} \quad (3)$$

The pore geometry of unity is usually assumed for unconsolidated sediments. However, pore geometry factor with high accuracy is realisable from log–log function between water resistivity formation factor F and porosity ϕ expressed in percentage in Eq. (3) as the intercept from the line of best fit. Mean value of m can be estimated from the slope of the function. Again, the expression in Eq. (3) can also be used to obtain different values of a if F, ϕ and m are known or m if F, ϕ and a are known.

Dakhnov (1962) used non consolidated sediments whose resistivity formation factor spans between 1 and 20 with porosity ϕ > 10% to develop theoretically, the expression in Eq. (4), which suggests a decrease in conductivity as porosity increases:

$$F = \frac{\left\{1 + 0.25(1-\phi)^{0.333}\right\}}{\left\{1 - (1-\phi)^{0.667}\right\}} \quad (4)$$

In an intergranular geomaterial, the pore throat is where two grains interact and link with larger pore volumes. The magnitudes of pore throats determine the conductivity and pore pressure properties in hydrogeological units. Archie cementation factor (m) measures the areal logarithm of pore throat to areal logarithm of pores in a geological unit. Cementation factor describes the mechanisms involving non connectivity between pores or increase in pore communication. This implies that m approaches unity when pore throats are closer to pore radius. According to Ehrlich et al. (1991), variations of m in the borehole are greatly caused by depositional subunit changes. Cementation factor demonstrates wide range of variations between samples, formations, and intervals within a geological medium and between formations. Cementation factor characteristically shows disparities within formations due to disparities in geometry of soil matrix and magnitude of pores (Atkins and Smith, 1961). There are many factors which influence cementation factors. These factors include: hydraulic radius, specific surface area, geometry and angularity of formation matrix and nature of soil formation matrix, grain arrangement, ease of fluid flow on the pore channel and grain surface, anisotropy, and overburden pressure. High fracturing is inversely proportional to the value of cementation factor according to Aguilera (1976), and large pore leads to high cementation factor (Lucia, 1983). Large angularity of grains leads to higher values of cementation factor. Increase in argillaceous materials and sedimentary heterogeneity elevates the value of cementation factor (Slater, 2007). Different pore systems cause variations of cementation factor. Large specific area of grains, caused by presence of fine-particle with high degree of anisotropy, can cause a rise in cementation factor. Geomaterials characterised by low pore connectivity, erratic geometry and complex conducting path, encounter high resistance to current flow, as a result of higher values of cementation factor and tortuosity (Liang et al., 2014).

The alterations of geohydrodynamic parameters in the lateral and longitudinal orientations of the subsurface reflect a high degree of variations in cementation factor. Induration or lithification of sedimentary formation leads to significant deviations in pore geometry system. Continued induration and lithification can deform the composing grains in rocks or any lithified geological formation. Moreover, pore irregularity, deformation, formation metamorphosis and low conductivity or high cementation factor can set in as a consequence (Carothers, 1968; Liang et al., 2014).

In mathematical sense, cementation factor can vary between one and infinity (Wyllie and Rose, 1950; Wyllie and Gregory, 1953; Olsen et al., 2008). However, in practice, cementation factor ranges between 1.30 and 3.00 according to Archie (1942). Keller (1982) different tabulated values of cementation factor prove that cementation factor cannot be fixed but vary with formation lithostratigraphy, permeability dependent factors and geologic age of geomaterials. Olsen et al. (2008) and Fadhil et al. (2013) also summarised different models for cementation factor. In documented materials the general range of cementation factor spans between unity in loose and fractured rocks (Aguilera, 1976; Jorgensen, 1988) and 5.12 for dense, hard and well indurated formations (Wyble, 1958). Specifically, the estimated cementation factors for various petrofacies are 1.09, 1.3, 1.3–1.6, 1.5–2.3, 1.8–3.0 and 1.8–4.2, for porous dolomites, glass spheres, homogeneous clean sands, heterogeneous sediments, compacted sandstones and limestones and argillaceous sandstones and siltstones respectively (Kirsch, 2009; Fadhil et al., 2013).

One of the geohydrodynamic parameters that relates inversely with formation hardness and geologic age of formation is the tortuosity factor (pore geometry factor, a) (Fadhil et al., 2013). Pore geometry factor reflects the shape of pores and the porosity a formation. Winsauer et al. (1952) who experimented on compacted sandstones realised a pore geometry factor of 0.62 and cementation factor of 2.15 (Humble equation) (see Eq. (5)).

$$F = \frac{0.62}{\phi^{2.15}} \quad (5)$$

In sediments of intergranular porosity, pore geometry factor of approximately unity is realisable (Keller and Frischkencht, 1966). For consolidated sandstones, Parkhomento (1967) obtained a pore geometry factor of 0.4. These values represent average values of pore geometry factors for the considered geomaterials. The wide variations associated with the measured values are caused by the heterogeneous nature of the formations (Fadhil et al., 2013).

Tortuosity (τ) is the ratio of the distance actually travelled by the fluid through the porous media to the assumed straight pore channel path. It predicts the shape of pores and the geometry of the pore paths. Tortuosity depends on the geometry, nature of grains size, non uniformity of pore grain orientations and type of pore grains and pore channels; mode of packing of the grains; grain size distribution; grains angularity, non-uniformity of the grains and hydraulic pressure.

For highly cemented geomaterials, which are lowly permeable and porous, tortuosity is higher because fluid flow is under pressure to cover a lengthy path. Lateral and horizontal changes in porosity and anisotropic variations and non-directional pattern of flow have a significant effect on this geohydrodynamic parameter.

This paper aims at the employment of constrained diagnostic models estimated from the joint analyses and interpretations of data of direct current resistivity measurements and hydrogeologic samples (soil and water) to assess the distribution of geohydrodynamic properties in parts of the arcuate Niger Delta of Nigeria, where saltwater–freshwater intrusion is common.