



Estimation of an unconfined sandy aquifer parameters using gravimetric and geoelectrical methods

^{1,2*}Yalo Nicaise, ¹d'Almeida Gérard F, ³Dovonou Flavien, ²Lawin A. Emmanuel and ¹Gnammi Yoro Ibrahim R.D

¹Department of Earth Sciences, University of Abomey-Calavi, 01BP4521 Cotonou, Benin

²Laboratory of Applied Hydrology (LAH) University of Abomey-Calavi, Benin

³Beninian Center of Scientific and Technical Research (BCSTR)

*Corresponding Author E-mail: yalonicaise@yahoo.fr

ABSTRACT

Estimation of hydrogeological parameters in a coastal sandy aquifer is not easy using pumping tests and drilling boreholes. Geophysical methods could be used in resolving this problem. Gravimetric method and Vertical Electrical Soundings have been used in this study. Hydrogeological parameters have been estimated for the shallow coastal aquifer. Thus, the average aquifer porosity is about 34%, the thickness of the aquifer is in the range of 19 – 21m, hydraulic conductivity about 4.6×10^{-2} m/s and transmissivity 3.91×10^{-4} m²/s. These parameters correlated well with calculated parameters using gravimetric method. The range of aquifer parameter values obtained using electrical method is a good indication of the reliability of this method. The electrical method has allowed estimating the aquifer parameters and could be used for mapping their spatial distribution.

Keywords: Electrical method, Gravimetric method, Vertical Electrical Soundings (VES), Porosity, Hydraulic conductivity, Transmissivity.

INTRODUCTION

Quantitative descriptions of the characteristic hydrogeologic parameters are necessary in efficient scientific and technical planning for management of groundwater resources. Many techniques of investigation are commonly employed with the aim of estimating the spatial distribution of aquifer parameters such as hydraulic conductivity, transmissivity and aquifer depth (Allen et al., 1997). The hydraulic characteristics of subsurface aquifers are important properties for both groundwater and contaminated land assessments and also for safe construction of civil engineering structures (Pantelis et al., 2007). The knowledge of hydraulic conductivity and transmissivity is essential for the determination of natural water flow through an aquifer (Kelly, 1977). As groundwater becomes more important as a source of uncontaminated water, improved hydrogeological knowledge, new groundwater exploration technologies and data processing methods must be efficient to facilitate investigations and evaluation of groundwater resources (Kosinski and Kelly, 1981). Specifically, resistivity techniques are well-established and widely used to solve a variety of geotechnical, geological and

environmental subsurface detection problems (deLima and Sharma, 1990).

Unfortunately, the standard techniques for the determination of aquifer hydraulic parameters such as well tests, permeameter measurements and grain size analysis are invasive, relatively expensive and either integrate over a large volume or only provide information in the vicinity of the borehole (Mendoza et al., 2003; Niwas et al., 2011). Conventional borehole techniques such as flow meter and slug tests for collecting hydrological data are costly, time consuming, and invasive; therefore a large effort has been undertaken to explore the potential of using geophysical data to compensate for the scarcity of in situ hydrological measurements (Rubin et al., 1992; Copty et al., 1993; Copty and Rubin, 1995; Hubbard et al., 1997; Rubin et al., 1998; Ezzedine et al., 1999; Hubbard and Rubin, 2000). According to MacDonald et al. (1999), interpolating aquifer properties between boreholes is often difficult with little or no data on which to base these extrapolations. On a coastal aquifer affected by salted water intrusion, just a few numbers of wells could be available for estimation of aquifer

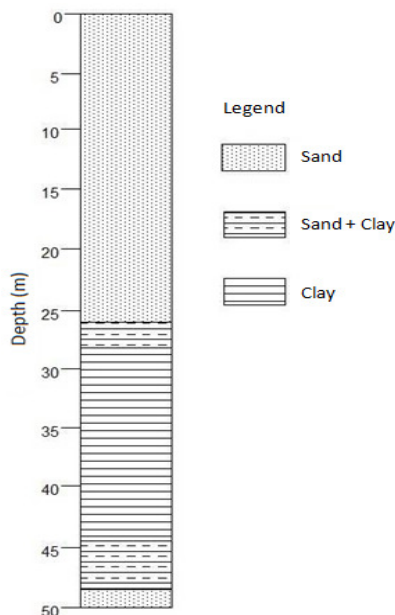


Figure 1. Lithology of PU2 well (Source: Maliki, 1993)

parameters. Therefore in areas with few pumping tests, the spatial distribution of aquifer properties cannot be confidently calculated.

Geophysical data used for hydrogeological characterization often include electrical resistivity (Kelly, 1977; Ahmed et al., 1988).

This paper is focused on the usefulness of geophysical measurements for porosity, hydraulic conductivity and transmissivity estimation and on the integration of hydrological and geophysical data.

The water bearing properties of rocks and earth materials such as porosity and specific yield depend on the shape, size arrangements, inter-connections, and extensiveness of the voids in which water can be accumulated and move (Karanath, 1994). Theoretically, grain size has no influence on porosity for uniform sized sediments which varies only with the packing arrangement of the grains (Mazac et al., 1985). Graton and Fraser (1935) based on results of a wide variety of sediment types showed qualitatively the tendency for porosity to decrease with increasing grain size. Specific yield is the storage term for an unconfined aquifer and is expressed as the ratio of the volume of water yielded from soil or rock by gravity drainage, after being saturated, to the total volume of the soil or rock (Schwartz and Zhang, 2003).

The geoelectrical method is an effective tool for ascertaining the subsurface geological framework of an area (Keller and Frischknecht, 1966; Griffith and King, 1965; Griffith, 1976; Kelly, 1977; Zohdy et al., 1974; Zohdy, 1989). Geoelectrical methods are based on the assumption that the rock matrix is generally an insulator and that an electrical current passes through because of the presence of water or moisture in the pores (Niwas et al., 2011). Application of the geoelectrical method has led researchers to develop surface

resistivity techniques for making quantitative estimates of water transmitting properties of aquifers (Tizro and Singhal, 1993).

MATERIAL AND METHOD

Study area

The measurements have been carried out on a site situated between the Atlantic Ocean and the coastal lagoon in south Benin. The climate in the South Benin is of transitional subequatorial type (Le Barbé et al., 1993). The annual pluviometric average is 1300 mm on our study zone. The temperature is on average of 27.7°C in dry season and 26.5°C in rainy season. Average temperature of water in the wells is around 26°C.

The littoral is as a whole made up of three sandy bars intersected with muddy levels. These sandy bars consist of accumulations of marine granular sediments, current or inherited of last quaternary transgressions (Laibi, 2011). We distinguish from north to south three generations of sandy bars (Oyédé, 1991): the intern bars of yellow sand, the median gray sand bars, and the current and sub actual brown gray sand bars. The intern bars of yellow sand are separated of the median gray sand bars by the Outobo lagoon. The median gray sand bars are separated from the subactual brown gray sand bars by the coastal lagoon. These various sand bars were studied by authors such as (Lang, 1988), (Tastet, 1977), (Pedersen et al., 2005), (Maliki, 1993) and (Boukari et al., 2009). The Quaternary unconfined coastal sandy aquifer, target of this study, is constituted of gray brown sand bar.

Table 1. ARCHIE LAW COEFFICIENTS (KELLER, 1988)

Types of grains or rocks	Coefficient m	Coefficient a	Porosity in %
Unconsolidated sand	1.37	0.88	25 à 45
Moderately cemented sedimentary rocks (sandstone and limestone)	1.72	0.62	18 à 35
Strongly cemented sedimentary rocks	1.95	0.62	5 à 25
Very porous volcanic rocks	1.44	3.50	20 à 80
Crystalline and metamorphic rocks	1.58	1.40	< 4
Types of grains or rocks	Coefficient m	Coefficient a	Porosity in %
Unconsolidated sand	1.37	0.88	25 à 45
Moderately cemented sedimentary rocks (sandstone and limestone)	1.72	0.62	18 à 35
Strongly cemented sedimentary rocks	1.95	0.62	5 à 25
Very porous volcanic rocks	1.44	3.50	20 à 80
Crystalline and metamorphic rocks	1.58	1.40	< 4

Table 2. Values of “m” by Doveton, 1986

Formation type	m value [-]
Unconsolidated sand	1.3
Very slightly cemented sandstone	1.4-1.5
Slightly cemented sandstone	1.5-1.7
Moderately cemented sandstone	1.8-1.9
Highly cemented sandstone	2.0-2.2

Hydrogeologic setting

The hydrogeologic setting consists of the aquifer of Quaternary (Boukari, 2002). This aquifer is the littoral or alluvial sandy aquifer of the Quaternary. The sandy bar contains the Quaternary shallow aquifer exploited by wells with flows between 1 and 15m³/h. It is an unconfined aquifer. The unsaturated zone approximately has a thickness of 0 to 3m (Boukari et al., 2009). According to Maliki (Maliki, 1993), the permeability of sands is raised enough, between 10⁻² and 10⁻⁴m/s. The depth of water level varies from 2,5m to 3,5m with an annual beat of the order of one meter. In practice, the fresh water can be exploited by wells or not very deep drillings far away from the offshore bar limits. According to SRHAU/BURGEAP (SERHAU-BURGEAP, 1987), the total porosity of littoral sands is around 35%.

The PU2 drilling data well in the study zone between the Atlantic Ocean and the coastal lagoon show that the shallow sand aquifer thickness does not exceed 30m (Figure 1). This shallow aquifer is collected by wells and drillings, with depth less than 30m, in which the water level is between 1m and 9 m. The water flow is between 1 and 15m³/h.

Methods of porosity estimation

Gravimetric method

The literature uses gravimetric measurements as a baseline to which other techniques are compared (Behren et al., 1995, M. Khardani et al., 2007, S. E. Foss et al., 2005, C. Pickering et al., 1993, Lazarouk et al., 1997, Herino et al., 1987). The total porosity is estimated by following formula (Equation 1), (François Schlosser, 1988):

$$\text{Porosity} = \phi = \frac{e}{1+e} \quad (\text{Equation 1})$$

$$e = \frac{V_v}{V_d}$$

With

Where V_v – volume of voids, V_d – dry volume and e – index of voids.

Geoelectrical method

Archie (1942) gave the following relation (Eq2) based on his works on the petrophysics of brine-filled rocks under clay-free condition.

Starting from Archie's (1942, 1950) equation for electrical resistivity (ρ):

$$\rho = a \rho_w \phi^m \quad (\text{Equation 2})$$

a – Electrical tortuosity parameter (Lynch, 1964) [-]

ρ_w – Resistivity of groundwater [Ohm m]

ϕ – Porosity of aquifer [-]

m – Cementation factor [-], see Table 1 for values. “ m ” is known as the cementation factor although it is interpreted as grain-shape or pore shape factor, and the coefficient a is associated with the medium and its value in many cases departs from the commonly assumed value of one.

Due to lack of core data from which the estimated values of “ a ” and “ m ” should, ideally, be examined for each site under investigation, an alternative approach reported in literature was adopted for porosity estimations (Worthington, 1993). In this regard, a forth expression in which the coefficient “ a ” has the value of one while “ m ” is allowed to vary from 1.3 to 2.5 used in log analysis, was suggested by Doveton, 1986 (Table 2). Archie (1942) observed that for clean unconsolidated sands packed in the laboratory, the value of “ m ” appears to be about “1.3”.

The inverted resistivity data were used to estimate the porosity from Equation (1) using literature values of respective parameters for an unconsolidated gravel-sand. Unconsolidated sediments are characterized by relatively low values of m (between 1.1 and 1.3) and parameter $a \approx 1$ (Keller, 1989; Schön, 2004), and we chose to use $a=1$ and $m=1.3$. The exponent m correlates with the sphericity $P=0.88$ of the sediment grains and follows an equation, $m=2.9-1.8P$ (Atkins and Smith, 1961; Jackson et al., 1978; Schön, 2004).

Methods of hydraulic conductivity estimation

Gravimetric method

Using Hazen (1905) Equation for intrinsic permeability (K_f):

$$K_f = N \times d_{10}^2 \quad \text{Equation (3)}$$

Where

N is Hazen's empirical coefficient.

d_{10} is the diameter of the 10 percentile grain size of the material

As pointed out by Lima and Niwas (2000) hydraulic conductivity, K (in m/s) is a more meaningful parameter which depends on both the type of formation and the fluid properties contained in it. To this end Nutting's equation Hubert, (1940) relates k_f to K as,

$$K = \frac{\delta_w g}{\mu} k_f \quad \text{Equation (4)}$$

Where

δ_w Water density [kg/m^3]

g Acceleration due to gravity [9.81 m/s^2]

μ Water dynamic viscosity [kg/m s].

Geoelectrical method

Heigold et al., (1979) combined Darcy's equation and Archie's equation to relate intrinsic permeability and porosity with limited success.

However, Heigold et al., (1979) showed a negative relationship ($K = 386.4\rho^{-0.93283}$) (Equation 5) between hydraulic conductivity (K) and aquifer resistivity (ρ) in Niantic-Illiopolis aquifer, a Wisconsinan out wash deposit by melt water from glacier in Central Illinois. The aquifer resistivity (ρ) was obtained using vertical electric sounding (VES).

The device used for the vertical electric soundings (VES) is of the Wenner type. This method makes it possible to obtain, according to the depth, the apparent resistivity of a certain volume of ground (Ghosh, 1971, Banerjee et al., 1980). Field data were interpreted through the following steps:

(a) matching the field curve with the standard curves of the auxiliary method (Marsden, 1973),

(b) preparing an initial geoelectrical model (thicknesses and corresponding resistivities) for a limited number of layers depending on the geological background as well as the borehole information in the study area, and

(c) entering the initial geoelectrical model into the geoelectric modeling package. Each VES was subjected to 1D-forward modeling, in which the iterative procedure was applied. Iterations were carried out to reach the best fit between the smoothed field curve and the calculated one.

The vertical electric sounding was established with 50m from the shore. The log of vertical electrical sounding underwent an inversion in the IPI2Win software. This inversion provides a model of geoelectrical distinct grounds.

Methods of transmissivity estimation

Gravimetric method

$$T = k * h \quad \text{Equation (6)}$$

Where, T is the transmissivity (m^2/s), k is the hydraulic conductivity (m/s) and h is water table in the unconfined aquifer (m).

Geoelectrical method

Using more basic Ohm's law of current flow and Darcy's law for horizontal fluid flow in a medium Niwas and Singhal (1981, 1985) derived two analytical equations,

$$T = \alpha S; \alpha = K\rho \quad \text{Equation (7)}$$

And

$$T = \beta R; \beta = K/\rho \quad \text{Equation (8a)}$$

respectively representing inverse and direct relationship between electrical resistivity and hydraulic conductivity, where;

T – Hydraulic transmissivity [m^2/s],

$R=hp$ – Transverse resistance [Ohm],

$S=h/\rho$ – Longitudinal conductance [S],

h – Thickness of the aquifer [m],

α, β constant of proportionality.

Analyzing these two equations further, Niwas et al. (2011) successfully solved the contradiction between direct and inverse relationship of electrical resistivity and hydraulic conductivity. Their analysis included data from Krauthausen test site in Germany fitted to analytical geoelectrical modeling results. They concluded that Equation (7) exists in case of highly resistive basement (S-dominant aquifer where electrical currents tends to flow horizontally) and Equation (8) exists in case of highly conducting basement (R-dominant aquifer where electrical currents tend to flow vertically).

RESULTS AND DISCUSSION

Determination of aquifer parameters Evaluation of porosity value using gravimetric method:

A sample of aquifer sediment was carried out for

Table 3: water density according to the temperature (After Handbook of Chemistry and Physics 64th ed.)

t_c (°C)	ρ_w (g/cm ³)	t_c (°C)	ρ_w (g/cm ³)
0	0,99987	45	0,99025
3,98	1,00000	50	0,98807
5	0,99999	55	0,98573
10	0,99973	60	0,98324
15	0,99913	65	0,98059
18	0,99862	70	0,97781
20	0,99823	75	0,97489
25	0,99707	80	0,97183
30	0,99567	85	0,96865
35	0,99406	90	0,96534
38	0,99299	95	0,96192
40	0,99224	100	0,95838

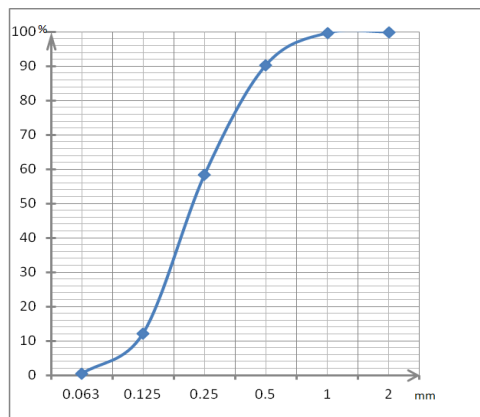


Figure 2: Grading curve for d_{10} determination

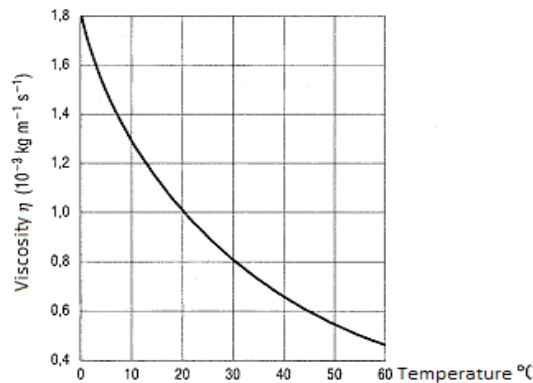


Figure 3: Viscosity according to temperature (After values of Dorsey, 1968)

analyses. After drying a soil sample using a drying oven with 105°C during 24h a weight of 204.71g (W_{dry}) was obtained. The weight of the sample saturated with water is of 246.9g (W_{sat}).

The total volume of voids (V_v) is:

$$V_v = \frac{W_{sat} - W_{dry}}{\rho_{water}} = \frac{246.9 - 204.71}{1000} = 42.19ml$$

$$V_d = \frac{W_{dry}}{\rho_s} = \frac{204.71}{2700} = 75.82ml$$

$$e = \frac{V_v}{V_d} = \frac{42.19}{75.82} = 0.55$$

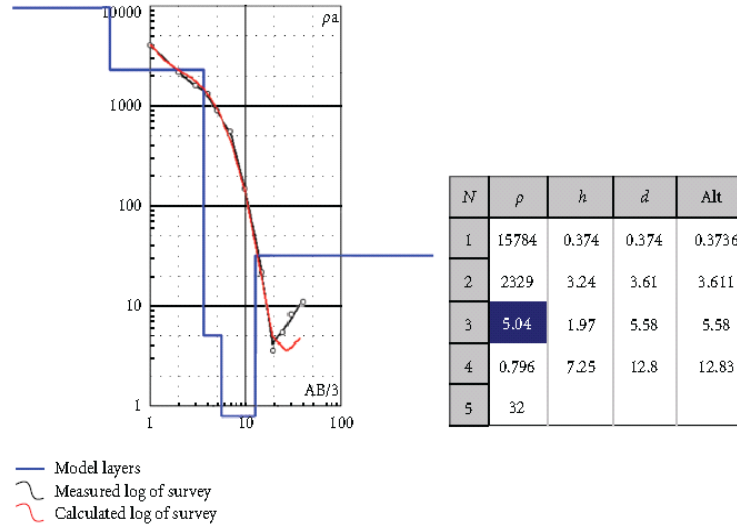


Figure 4. Log of Survey on the study area (Source: Yalo et al., 2012)

$$\phi = \frac{e}{1 + e} = \frac{0.55}{1.55} = 35.48\%$$

The total porosity value is: ϕ
 $\Phi = 35.48\%$

Evaluation of porosity value using electrical method:

Knowing that the aquifer is primarily sandy on a thickness of approximately 26m, according to the log of drilling (fig.4), the values of 1.37 and 0.88 were retained respectively for "m" and "a" and the weak variation of porosity could be neglected.

$$\rho_f = F(\rho_w) \quad \text{(Equation 2b)}$$

With "a", "m", and $\phi = \text{Constant}$

The value of porosity ϕ was estimated on a ground saturated with sea water. The measured conductivity ρ_w of sea water being 50.700μS/cm or 0.2ohm.m and the measured resistivity of $\rho_f = 0.8 \text{ ohm.m}$, porosity were calculated according to the following equation:

$$\phi = \left(\frac{a\rho_w}{\rho_f} \right)^{1/m} \quad \text{(3)} \quad \text{(Equation 2c)}$$

This estimation gives a value of 34% for the total porosity of sands.
 $\Phi = 34\%$

Evaluation of hydraulic conductivity value using gravimetric method:

$$K_f = N \times d_{10}^2 \quad \text{Equation (3)}$$

Bear and Verruijt (1987) give N is usually taken as $100 \text{ m}^{-1} \text{ s}^{-1}$, with d in mm and K in m/s.
 d_{10} is the diameter of the 10 percentile grain size of the material. D_{10} has been obtained using grading curve of soil sample.
 $K_f = 1.44 \text{ m/s}$

$$K = \frac{\delta_w g}{\mu} k_f \quad \text{Equation (4)}$$

The water density and viscosity have been taken for a temperature of 26°C (Table 3) and (Figure 3).

Calculated value for hydraulic conductivity is:
 $K = 1.6 \cdot 10^{-3} \text{ m/s}$

Evaluation of hydraulic conductivity value using geoelectrical method:

$$K = 386.4\rho^{-0.93283} \quad \text{(Equation 5)}$$

Resistivity of layer was obtained using the vertical electric sounding (VES). Only top layer has been taken into account because its depth is similar with the soil sample depth. Figure 4

$K = 4.6 \cdot 10^{-2} \text{ m/s}$ for $\rho = 15784 \text{ ohm.m}$ on VES

Evaluation of transmissivity value using geoelectrical method:

$$T = k * h \quad \text{(Equation 6)}$$

According to Maliki (Griffith, 1976), the permeability of sands is raised enough, between 10^{-2} and 10^{-4} m/s. The depth of water level varies from 2,5m to 3,5m with an annual beat of the order of one meter.

$$T = 1.6 \cdot 10^{-3} \times 3.5 = 5.6 \cdot 10^{-3} \text{ m}^2/\text{s}$$

$$T = 5.6 \cdot 10^{-3} \text{ m}^2/\text{s}$$

Evaluation of transmissivity value using gravimetric method:

The log of survey shows a highly conducting basement so R-dominant aquifer where electrical currents tend to flow vertically.

In this case the transmissivity is leading by transverse resistance.

$$T = \beta R \beta = K/\rho \quad (\text{Equation 8a})$$

$$R = h \text{ thus ;}$$

$$T = \frac{K}{\rho} \sum_{i=1}^n h_i \rho_i$$

(Equation 8b)

For a water table of 3,61m (Figure 3), $T = 2.91 \cdot 10^{-6} \times 13449 = 39.1 \cdot 10^{-3} \text{ m}^2/\text{s}$

$$T = 39.1 \cdot 10^{-3} \text{ m}^2/\text{s}$$

Correlation between gravimetric and electrical aquifer properties

The values of the aquifer parameters obtained using the electrical method approach, were compared to those obtained by the gravimetric method. Electrical method defines a total porosity lower (1.9%) than that obtained by the gravimetric method and a hydraulic conductivity and a transmissivity higher (respectively of 0.004 m/s and 0.03 m²/s). Indeed the obtained parameters using the electrical method range in the interval of the values for a sandy aquifer like that of the Quaternary. For sandy aquifers, Keller, 1988 has defined an interval of porosity ranging between 25 – 35%. Castany, 1982 has defined an interval of hydraulic permeability ranging between 10^{-3} – 10^{-4} m/s for a free clay sandy aquifer with uniform grain size distribution. Using pumping tests, Maliki found that the permeability of sands is raised enough, between 10^{-2} and 10^{-4} m/s. The values of transmissivities for free clay sandy aquifers lie between 10^{-3} and 10^{-4} m²/s. Thus, all the obtained aquifer parameter values using the electrical method are included in the definite standards on the one hand and are very close to those obtained by the gravimetric method on the other hand. The electrical method is noninvasive and not time-consuming. Actually, the electrical measurements on the ground do not disturb the medium. On the other hand, the gravimetric method requires a sampling which alters the ground. The sample must then be preserved and transported to the laboratory where it will

be analysed. The conditions of conservation of the sample can influence the results of the analyses. An electric survey can be carried out only in few minutes or few hours according to the depth of investigation while the drying of one sample must spend one day. The formulas of Archie for the calculation of porosity, those of Heigold for the calculation of electric conductivity and that of Niwas and Singhal for the transmissivity appeared effective for the estimation of the unconfined sandy aquifer parameters. Kelly and Frohlich (1985) rejected the negative relationship established by Heigold et al., (1979), with the reason that for correlation, only three data points were used that are not sufficient to generalize any relationship and showed again a positive correlation between them. The result of this study makes it possible to add the electrical method to those able to estimate coastal sandy aquifer parameters. Contrary to the wells which cannot be drilled everywhere especially in coastal zone, electrical surveys can be realized on a whole zone of study in order to consider spatial distribution of the aquifer parameters.

CONCLUSION

In this paper, we try to use electrical method for hydraulic parameter estimation in the case of clay free sandy coastal aquifer. Archie, Heigold and Niwas equations have been used to compute respectively porosity, hydraulic conductivity and transmissivity of the unconfined sandy aquifer. Since the spatial distribution of aquifer properties cannot be confidently calculated in areas with few pumping tests, determination of aquifer parameters from geoelectric sounding becomes a good alternative and cost-efficient technique since drilling of wells to evaluate aquifer parameters can be both expensive and time-consuming. The estimated porosity value (34%), hydraulic conductivity value (4.6×10^{-2} m/s) and transmissivity (39.1×10^{-3} m²/s) correlated well with calculated parameters using gravimetric method. The range of aquifer parameters values obtained from VES interpretation is a good indication of the reliability of this method.

The results give a useful estimation of the aquifer parameters and electrical method could be used as an additional method for estimation of aquifer parameters in the area where pumping tests are not available.

ACKNOWLEDGEMENTS

We are grateful to the Applied Hydrology Laboratory of Benin and Hydraulic transfers Laboratory of Grenoble (France). Authors are thankful for the financial support of AIRD through the JEA1 AQUI BENIN project. We also thank Professor Silliman Stephen of Gonzaga University (USA) for his collaboration.

REFERENCES

- Ahmed S, De Marsily G, Talbot A (1988). Combined use of hydraulic and electrical properties of an aquifer in a geostatistical estimation of transmissivity, *Ground Water*, 26(1):78–86.

- Allen DJ, Brewerton LJ, Coleby LM, Gibbs BR, Lewis MA, MacDonald AM, Wagstaff SJ, William AT(1997). The physical properties of major aquifers in England and Wales. British Geological Survey Technical Report WD/97/34.
- Archie G (1950) Introduction to petrophysics of reservoir rocks. AAPG Bulletin 34, 943–961.
- Archie GE (1942). The electrical resistivity log as an aid in determining some reservoir characteristics. Trans. Am. Inst. Min. Metall. Eng. 146:56 – 62.
- Atkins ER, Smith GH(1961). The significance of particle shape in formation resistivity factor porosity relationships. J. Petrol. Technol. 13:285–291.
- Banerjee B, Sengupta BJ, Pal BP (1980). "Apparent resistivity of multilayered earth with a layer having exponentiality varying conductivity," Geophysical Prospecting, 28(3):435–452..
- Bear J, Verruyt A (1987). Modelling Groundwater Flow and Pollution. Reidel Publishing Co., Dordrecht, Holland: Pp. 414.
- Boukari M (2002). "Reactualization of hydrodynamic knowledge relating to the Coastal Sedimentary Basin of the Benin," Sup-port to the Water Stock Management Report (WSMR), Cotonou, Benin.
- Boukari M, Alassane A, Azonsi F(2009). Evaluation by DRASTIC method of the of the Cotonou groundwater vulnerability (South Benin, West Africa) Publication: Africa Geoscience Review. Volume 16, Number 3.
- CASTANY (1982): Principes et méthodes de l'hydrogéologie. Dunod. F 7512
- Copty N, Rubin Y (1995). A stochastic approach to the characterization of lithofacies from surface seismic and well data, *Water Resour. Res.*, 31(7):1673–1686.
- Copty N, Rubin Y, Mavko G (1993). Geophysical-hydrological identification of field permeabilities through bayesian updating, *Water Resour. Res.*, 29(8):2813–2825.
- deLima OAL, Sharma MM(1990). A grain conductivity approach to shaly sands. *Geophysics*, 50:1347-1356. <http://dx.doi.org/10.1190/1.1442782>
- DORSEY NE(ed.) (1968). Properties of Ordinary Water-Substance. New York: Hafner Publications.
- Doveton JH(1986). Log Analysis of Subsurface Geology. Wiley, New York.
- Ezzedine S, Rubin Y, Chen J(1999). Hydrological-geophysical Bayesian method for subsurface site characterization: Theory and application to llnl superfund site, *Water Resour. Res.*, 35(9): 2671–2683.
- Foss SE, Kan PYY, Finstad TG (2005). "Single beam determination of porosity and etch rate in situ during etching of porous silicon," J. Appl. Physics. 97(11):114909,
- François Schlosser (1988). Eléments de mécanique des sols. Presse de l'Ecole Nationale des Ponts et Chaussées. Paris ISBN 2-85978-104-8. Pp. 271.
- Ghosh DP(1971). "Inverse filter coefficient for the computation of apparent resistivity standard curves for horizontally stratified earth," *Geophys Prospect*, 19:769–775.
- Graton LC, Fraser HJ (1935). Systematic packing of spheres with particular relation to porosity and permeability. J. Geol. 43: 785–909.
- Griffith DH (1976). Application of electrical resistivity measurements for the determination of porosity and permeability in sandstones. *Geoexploration* 14 (3/4):207–213.
- Heigold PC, Gilkeson RH, Cartwright K, Reed PC (1979). Aquifer transmissivity from surficial electrical methods. *Groundwater* 17:330–345.
- Herino R, Bomchil G, Barla K, Bertrand C, Ginoux JL (1987). "Porosity and pore size distributions of porous silicon layers," J. Electrochemical Society.134(8):1994–2000.
- Hubbard S, Rubin Y (2000). Hydrogeological parameter estimation using geological data: A review of selected techniques, *J. Contam. Hydrol.*, 45:3–34.
- Hubbard S, Rubin Y, Majer E (1997). Ground penetrating radar assisted saturation and permeability estimation in bimodal systems, *Water Resour. Res.*, 33(5):971–990.
- Hubert MK (1940). The theory of groundwater motions. Journal of Geology 48:785–944.
- Jackson PD, Taylor D, Smith PM (1978). Standard resistivityporosity–particle shape relationships for marine sands. *Geophysics* 43:1250–1268.
- Karanath KR (1994). Hydrogeology. Mc Graw-Hill Publishing Co. Ltd, Pp. 458.
- Keller GV (1988). Rock and mineral properties. In Electromagnetic methods in Applied Geophysics, vol. 1, Nabighian, M., Editor. Society of Exploration Geophysicists. Vol. 2: Applications, Chapter 6, M. N. Nabighian (editor), Soc. Expl. Geophys. Publication, Pp. 427 – 520
- Keller GV (1989). Electrical properties. In: Carmichael, R.S. (Ed.), Practical Handbook of Physical Properties of Rocks and Minerals. CRC Press, Boca Raton.
- Keller GV, Frischknecht FC (1966). Electrical Method in Geophysical Prospecting. Pergamon Press, Oxford, Pp. 517.
- Kelly WE, Frohlich R (1985). The relation between transmissivity and transverse resistance in a complicated aquifer of glacial outwash deposits. *J. Hydrology* 79:215 – 219.
- Kelly WE.(1977). Geoelectric soundind for estimating aquifer hydraulic conductivity. *Groundwater*, 15 (6):420-425. <http://dx.doi.org/10.1111/j.1745-6584.1977.tb03189.x>
- Khardani M, Bouaïchaand M Bessaï B (2007). "Bruggeman effective medium approach for modelling optical properties of porous silicon: comparison with experiment," *physica status solidi (c)* ,4(6):1986–1990,
- Kosinki WK, Kelly WE (1981). Geoelectric soundings for predicting aquifer properties. *Ground Water* 19:163 – 171.
- Laibi RA (2011). "Quaternary evaluation and current dynamics of the Mono-Couffo estuary cords barriers in the littoral of Benin" (Gulf of Guinea, West Africa). Thesis of Doctorate, University of the Littoral Coast Opal, Dunkirk, France.
- Lang J, Paradis G, et Oyédé LM (1988). Margino-littoral field of Benin (Gulf of Guinee West Africa) : Eocene sequence and maine deposits of « Yellow sands ». J. African Earth Sci. Vol. 7(5/6).
- Lazarouk S, Jaguiro P, Katsouba S, Maiello G, Monica SL, Masini G, Proverbio E, Ferrari A (1997). "Visual determination of thickness and porosity of porous silicon layers," *Thin Solid Films*. 297(1 – 2): 97-101, Apr.
- Le Barbé L, Alé G, Millet B, Borel Y, Gualde R (1993). Shallow water ressources in Republic of Benin. Orstom éditions, French Institut of Research for development, Paris, Direction of Hydraulic, Benin, Cotonou.
- Lima OAL, Niwas Sri (2000). Estimation of hydraulic parameters of shaly sandstone aquifers from geoelectrical measurements. *J. Hydrology* 235:12–26.
- Lynch EJ (1964). Formation Evaluation. Harper and Row Publishers Inc., New York.
- MacDonald AM, Burleigh J, Burgess WG (1999). Estimating transmissivity from surface resistivity soundings: an example from the Thames Gravels. *Quarterly J. Eng. Geol.* 32:199 – 205.
- Maliiki R (1993). Hydrogeologic study of the beninian littoral in the area of Cotonou (A.O.). Thesis of Doctorate of the 3rd cycle. UCAD; Dakar, Senegal. Pp. 162.
- Marsden D (1973). "The automatic fitting of a resistivity sounding by a geometrical progression of depth," *Geophysical Prospecting*, 21(2): 266–280.
- Mazac O, Kelly WE, Landa I (1985). A Hydrogeophysical model for relation between electrical and hydraulic properties of aquifers. *J. Hydrol.* 79:1–19.
- Mendoza FG, Steenhuis ST, Todd Walter M, Parlange JY (2003). Estimating basin-wide hydraulic parameters of a semi-arid mountainous watershed by recession-flow analysis. *J. Hydrology* 279:57 – 69.
- Niwas S, Tezkan B, Israil M (2011). Aquifer hydraulic conductivity estimation from surface geoelectrical measurements for Krauthausen test site, Germany. *Hydrogeol. J.* 19:307 – 315.
- Niwas S, Tezkan B, Israil M (2011). Aquifer hydraulic conductivity estimation from surface geoelectrical measurements for Krauthausen test site, Germany. *Hydrogeol. J.* 19:307–315.
- Niwas Sri, Singhal DC (1981). Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. *J. Hydrology* 50:393–399.
- Niwas Sri, Singhal DC (1985). Aquifer transmissivity of porous media from resistivity data. *J. Hydrology* 82:143–153.
- Niwas Sri, Tezkan B, Israil M, 2011. Aquifer hydraulic conductivity estimation from surface geoelectrical measurements for Krauthausen test site, Germany. *Hydrogeol. J.* 19, 307–315.
- Oyédé L M (1991). "Current sedimentary Dynamics and recorded messages in the quaternary sequences and neogene of the margino-littoral field of Benin (West Africa). Thesis of doctorate new mode, University of Bourgogne and National University of Benin.

- Pantelis MS, Maria K, Filippou V, Antonis V, George S (2007). Estimation of aquifer hydraulic parameters from surficial geophysical methods. *J. Hydrology*, 338:122-131. <http://dx.doi.org/10.1016/j.jhydrol.2007.02.028>
- Pickering C, Canham L, Brumhead D(1993). "Spectroscopic ellipsometry characterisation of light-emitting porous silicon structures," *Applied Surface Science*. 63(1-4):22–26.
- Rubin Y, Hubbard S, Wilson A, Cushey M (1998). Aquifer characterization, in *The Handbook of Groundwater Engineering*, edited by J. W. Delleur, CRC Press, Boca Raton, Fla.
- Rubin Y, Mavko G, Harris J (1992). Mapping permeability in heterogeneous aquifers using hydrologic and seismic data, *Water Resour. Res.*, 28(7):1809–1816.
- Schön JH (2004). *Physical Properties of Rocks*. Elsevier, Amsterdam.
- Schwartz FW, Zhang H (2003). *Fundamentals of Groundwater*. John Wiley and Sons Publication, New York, Pp. 574.
- SERHAU-BURGEAP (1987). Experimentation on the drying in Cotonou: potentiality of infiltration in the ground. FAC, France, MET, Benin.
- Tastet J P (1977). " The Quaternary to actual sedimentary formations of Togo and Popular Republic of Benin littoral, " Supplement of the Bulletin AFEQ . 50:155 –167.
- Tizro TA, Singhal DC (1993). Geoelectrical studies in Narnaul area for estimating transmissivity of alluvial aquifers. National seminar on hydrological hazards- Prevention-Mitigation. Univ. Roorkee, India.
- von Behren J, Tsybeskov L, Fauchet PM (1995). "Preparation and characterization of ultrathin porous silicon films," *Applied Physics Letters*. 66.(13):1662–1664.
- Williams Gardner S, Hazen Allen (1905). *Hydraulic Tables*. New York:Wiley.
- Worthington PF (1993). The uses and abuses of the Archie equations: I. the formation factor - porosity relationship. *J. Appl. geophysics* 30:215 – 228.
- Yalo N, Descloitres M, Alassane A, Mama D, Boukari M (2012). Environmental Geophysical Study of the Groundwater Mineralization in a Plot of the Cotonou Littoral Zone (South Benin). Hindawi Publishing Corporation International Journal of Geophysics Volume 2012, Article ID 329827, 10 pages: 1-10. doi:10.1155/2012/329827
- Yalo N, Descloitres M, Vouillamoz J-M, Alle C (2013). Delimitation of salt water wedge in shallow coastal aquifer by TDEM method at Togbin (South Benin) *Int. J.Sciences and Advanced Technol.* 3 (3): 21 – 29. (ISSN 2221-8386)
- Zohdy AAR (1989). A new method for automatic interpretation of Schlumberger and Wenner sounding curves. *Geophysics* 5 (2):245–252.
- Zohdy AAR, Eaton GP, Mabey DR (1974). Application of surface Geophysics to groundwater investigations. US Geological Survey Techniques of Water- Resources Investigations, Book 2. Pp. 116 (Chapter D1).

How to cite this article: Yalo N., d'Almeida G.F., Dovonou F., Lawin A.E. and Gnammi Y.I.R.D (2014). Estimation of an unconfined sandy aquifer parameters using gravimetric and geoelectrical methods. *Int. Res. J. Geo. Min.* 4(1): 20-28