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Study of the quaternary aquifer of Abidjan through hydrodynamic parameters evaluation

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Abstract— The quaternary aquifer of Abidjan city, is often subjected to pollution because groundwater occurs at shallow depths (<6 m). However, this water is increasingly sought by one part of the population. Unfortunately the properties of this aquifer are not well known to define a management plan. This work aims to study quaternary aquifer through the hydrodynamic properties determination (porosity, saturated and unsaturated hydraulic conductivity and water retention curve) by prediction methods (Kozeny Carman, Kovac's modified and Brooks and Corey).The methods for predicting hydrodynamic properties tested gave good results. These methods have the advantage of using the physical properties of soil easy to measure. This is an original approach to the study of the hydrodynamic properties of the very extensive aquifers like the quaternary aquifer of Abidjan. These parameters are difficult to measure in situ.This work also highlighted risk areas for human settlements and infrastructure construction. Indeed, it is created permanent moisture above the water table in the fine sands. This moisture is the result of capillary rise which is important in fine soil particles.

Index Terms— saturated and unsaturated hydraulic conductivity, water retention curve, Kozeny Carman model, Kovac's modified model, Brooks and Corey, hydrodynamic properties, aquifer of quateranary, Abidjan.

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1. INTRODUCTION

Coastal zones are strategic zones for human activities. It is estimated that 50-70% of the global human population lives in these coastal zones [1]. This is the case of Africa. Major African cities are located on the coast. The urbanization rate in West Africa was 37% in 2006 [2]. The mismatch between increasing urbanization and the establishment of basic services is a problem for development. One of the problems which these coastal countries face is water supply to the population [3]. Yet, these countries, particularly the countries of West Africa have large aquifers. However, groundwater of these aquifers is faced with several problems. For example, the exploitation of groundwater in Togo, Nigeria and Benin causes a rise of salt water intrusion into fresh water aquifers [4], [5], [6]. Groundwater pollution by human activities in Africa has been reported by [7], [3].

These problems affect the groundwater quality of these aquifers. Few studies have been conducted on these aquifers to know their functioning and to define a management plan. This is the case of the quaternary aquifer of Abidjan. This Quaternary aquifer is located in the southern part of Abidjan city. It is an unconfined aquifer. The use of water from this aquifer by the populations is made by sumps and traditional wells. The studies showed a strong anthropogenic pollution [8], [7]. Attempts to build a model of water and solute transfers have been hampered by lack and reliability data including hydrodynamic parameters (saturated and unsaturated hydraulic conductivities and water retention curve). In situ measurement of these parameters is difficult and costly because the site is extensive [9].

Methods for prediction of hydrodynamic parameters have been successfully tested and exist in the literature [10], [11], [12], [13], [14], [15].

This work aimed at studying the Quaternary aquifer of Abidjan through the determination of hydrodynamic properties. The hydrodynamic parameters on the entire Quaternary aquifer were determined. The predictive models have been tested.

2. MATERIALS AND METHODS

2.1 Study Site

The study area is located in West Africa. It is in the South of Côte d'Ivoire. It covers the area between latitude 5°12'5''N and 5°20'15''N and longitude 4°4'57''W and 3°43'19''W. It is divided into five municipal zones, namely Treichville, Marcory, Koumassi, Port-Bouët and Grand-Bassam (Fig.1). The population is estimated at 880 712 inhabitants [16]. The study area is located in the coastal sedimentary basin and covers 253 km^2 and is characterized by a flat relief. Various geological formations of Quaternary age are found in this zone.

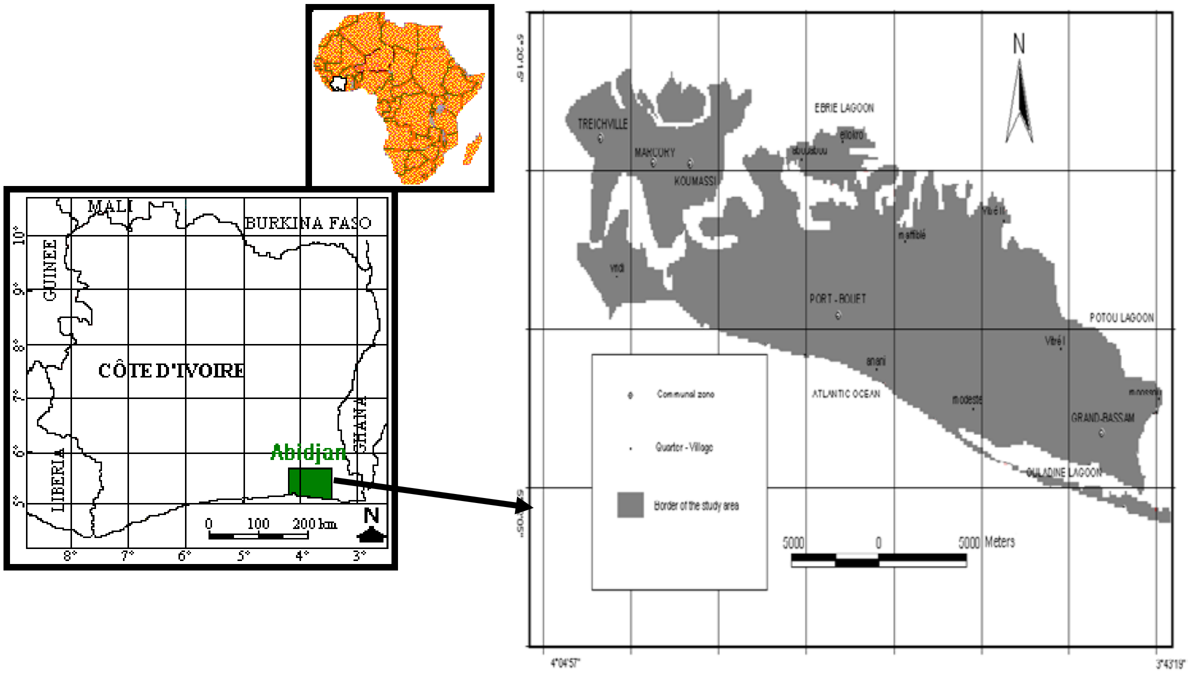

Fig.1. Geographic description of the study area

2.2 Measurements

2.2.1 Porosity measurements and particle size analysis

Fifty one (51) soil samples have been collected across the site. The sampling points are shown in fig. 2.

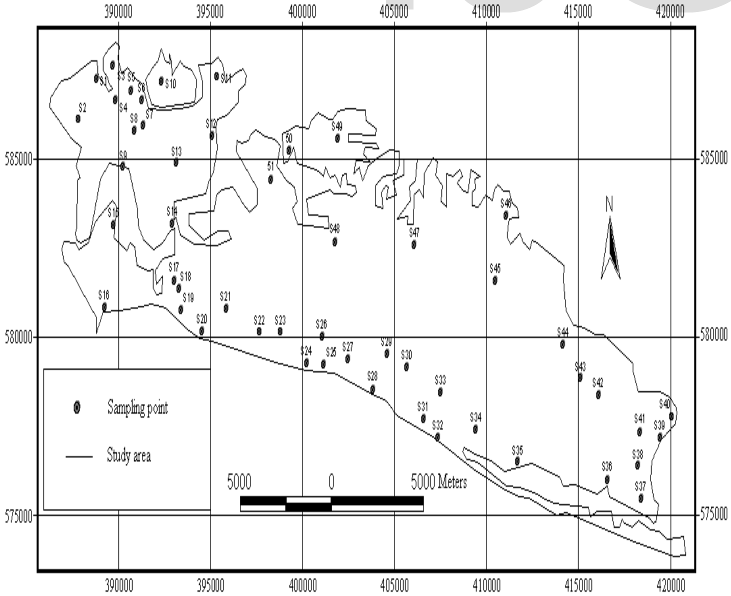

Fig. 2: Location of sampling points

Porosities have been measured and particle size analysis has been performed on the soil samples. Hydraulic conductivity measurements have been implemented by using the double rings infiltrometer at some sampling points.

For measuring porosity (n), a volume V of the dried sample has been taken and submerged in a volume of water (Ve) in a sealer chamber for one day until it became saturated. The volume of the pores is equal to the volume of water Ve minus the volume (Vre) of the remaining water after the soil sample is saturated [17], [15]. The porosity (n) was computed using the following equation:

$$n = (Ve - Vre)/V \quad (1)$$

Care was taken in making sure these samples are representative of important patterns of particle-size distribution in soils of the study area. In these samples, particles < 63 µm (i.e., silt and clay components) were uncommon. Organic matter was removed using 30% H_2O_2. The sand fraction (> 63 µm) was dried and processed by dry sieving technique. The sample was placed on top of a series of 16 AFNOR sieves stacked in order of decreasing mesh sizes. The refusal of each sieve is weighed after agitation. We deduce the percentage by weight of each size class compared to the initial sample. The particle size curves are made from cumulative percentages of different class. The diameters D10 and D60 are determined on the particle size curves.

2.2.2 Saturated hydraulic conductivity and the water content measurement

A double ring infiltrometer was used for measuring saturated hydraulic conductivity of unsaturated zone at 51 sites. This method has already been used by [18] and [19].

Litter was cleared from 1.5-1.5 m^2 area, on soil surfaces that were not disturbed and metal rings (inner 13 cm diameter, outer 30 cm diameter, height 25 cm) were driven vertically into the soil for about 10 cm so that the smaller ring was centered in the larger ring, using a hammer. Both rings were partially filled with water, thereby maintained a constant liquid level. The volume of water added from the graduated cylinder into the infiltration rings to keep the water levels constant is equal to the measure of the volume of liquid that infiltrates into the soil. The volume of water infiltrated (V) during the time (t) intervals is converted into an infiltration velocity. The average infiltration velocity of the test is equivalent to infiltration rate. Knowing the infiltration flow rate q, the law of Darcy is applied. The infiltration surface (S) is the section of the cylinder. The hydraulic conductivity (ks) is determined in the equation (2).

$$Ks = V\ /St \qquad (2)$$

Where ks is hydraulic conductivity (ms^{-1}); V, the infiltrated water volume (m^3); S, the water section of the cylinder (m^2) and t is time (s).

Six wells were carried out on site at the sampling points S2, S17, S25, S35 and S48. During the implementation of wells, soil samples have been taken at different levels. These samples protected from sunlight have been transported to the laboratory. They have been put into the oven for 24 hours to measure the water content.

2.3 Prediction methods of saturated and unsaturated hydraulic conductivity and water retention curve

2.3.1 The Kozeny Carman method (KM)

Based on the method of Kozeny-Carman, [20] and [21] developed a model for estimating the saturated hydraulic conductivity. This model is derived from the relationship proposed by [22]. They have introduced a parameter that is the tortuosity which is a function of the void ratio.
Thus the general equation is:

$$Ks = C(\gamma/\mu\,)(e^{(3+x)}/1+e)(1/(\varphi s^2\ Sm^2) \qquad (3)$$

With C constant; γ, the specific gravity of water ($kg/m^2/s^2$); μ, the viscosity of water (kg/m/s); e, void ratio calculated from the measured porosity (n) as follows:

$$e = n\ /(1-n) \qquad (4)$$

x=2 is a factor that takes into account the tortuosity; φs, the density of water (kg/m^3) and Sm, the specific surface area (m^2/kg).
According to [12], the specific surface area can be written as:

$$Sm = \alpha/(\varphi s\ Dh\ ) \qquad (5)$$

Where α is shape factor, $1/\alpha^2=1$ and Dh the equivalent diameter (m).
According to [13], we can write:

$$\mathrm{Dh} = \mathrm{Cu}^{1/6}\mathrm{D10} \qquad (6)$$

The final form of the equation can be written for low plasticity soils taking into account the geotechnical parameters as follows [21]:

$$Ks = Cg(\gamma\ /\ \mu)(e^{3+x}\ /1+e)C_u^{1/3}D_{10}^2 \qquad (7)$$

With $Cg = 0.1$, $\gamma_w = 10KN/m^3$, $\mu_W = 10^{-3}\,Pa.s$, $D10$ (m), Cu uniformity coefficient, and ks (m/s).

2.3.2 Modified kovac's model (MK) for predicting the Water retention Curve (WRC)

Modified kovac's model (MK) comes from the Kovac's model. Kovac's model considers water held by capillary forces responsible for a capillary saturation, Sc, and by adhesive forces responsible for saturation by adhesion, Sa [12]. The modified kovac's model (MK) is based on WRC estimation of incompressible materials, under drainage conditions using basic geotechnical properties [24], [25], [20], [24]. In the MK model formulation, WRC is the function of Sc and Sa. Sa is the main component of WRC at low suction values, whereas the Sa is dominant at higher suction. The WRC is expressed by a series of equations presented as follows:

$$Sr=\theta/n=1-\langle 1-Sa\rangle\ (1-Sc) \qquad [8]$$

$$Sc = \ [1-(hco/\psi)^2+1]^m\ exp[-m(hco/\psi)^2] \qquad [9]$$

$$Sa = ac[1-[\ln(1+\psi/\psi r)/\ln(1+\psi o)][(hco/\psi n)^{2/3}/((e^{1/3})\ \ (\psi/\psi n^{1/6}))] \qquad [10]$$

Sr expresses the total degree of saturation with θ the volumetric water content and n the porosity of materials. The Macauley brackets $\langle - \rangle$ are defined as $\langle x\rangle = 0.5(x+|x|)$. Sc and Sa are respectively the capillary and adhesion components. In these equations hco is the equivalent capillary height defined as a reference parameter. It depends on the solid surface area Sm. In the granular materials hco is expressed as follows:

$$hco = 0.75/[1.17\log(Cu)+1]eD10 \qquad [11]$$

Where,
D10 and D60 are diameters corresponding respectively to 10% and 60% on the cumulative grain size distribution curve and Cu is the uniformity coefficient (Cu=D10/D60);
hco, D10, D60 and ψ (the matric suction head) are expressed in centimeters;
m is the pore size coefficient and is defined as a function of grain size distribution;
e is the void ratio of materials;
ψn is a normalized parameter; ψn=1 cm when the suction is given in centimetres;
ac is the adhesive coefficient and controls the adhesion saturation.

Assuming thermodynamic equilibrium, Sa induces a water content of Zero at ψ0, θ=0 at Ψ= Ψ0=102 cm water [25].

According to the applications of MK model carried out on a variety of different granular soils, m can be approximately expressed as m=1/Cu and ac approximately constant (ac=0.01 when suction is expressed in centimetres) [24]. ψr is the residual suction and is expressed from the equivalent capillary height hco as follows :

$$\Psi_r = 0.8hco^{1.2} \qquad (12)$$

2.3.3 Brook and Corey model for predicting unsaturated hydraulic conductivity (Kuns)

Many models have been proposed to predict the unsaturated hydraulic conductivity (Kuns) [26], [27], [28], [14]. These models are sometimes empirical relationships between unsaturated hydraulic conductivity and water content of the soil. This is the case of the model of Brook and Corey. This model describes kuns as a function depending on the suction. It is expressed in the following equation:

$K_{UNS}(\psi) = Ks$ for $\psi \leq \psi a$ (13)

$K_{UNS}(\psi) = Ks(\Psi a/\Psi)^{\eta}$ for $\psi > \psi a$ (14)

with ψ a matric suction (cm); ψa, the air entry value (cm); ks is the hydraulic conductivity in saturated conditions (m/s); η, an empirical constant. The constant η is determined from the water retention curve.

The retention curve can be described by the following equation:

$\theta(\psi) = \theta s(\Psi a/\Psi)^{\lambda}$ for $\psi > \psi a$ (15)

With θ the volumetric water content; θs, the volumetric water content at saturation; λ, the index of pore size distribution; λ is the slope of the water retention curve.

$\lambda = \Delta\log(\theta)/\Delta\log(\psi)$ (16)

And $\eta = 2 + 3\lambda$ (17)

2. RESULTS

3.1 Physical and hydraulic conductivity properties

Void ratios e calculated from the measured porosities n, the diameters D10 and D60 and Cu obtained and calculated ks are presented in Table 1.

TABLE.1: PHYSICAL PROPERTIES AND SATURATED HYDRAULIC CONDUCTIVITY

Points	n	e	$D10.10^{-2}$ (m)	$D60.10^{-2}$ (m)	Cu	ks(m/s) predicted
S1	0,29	0,40	0,020	0,060	3,00	4,22E-05
S2	0,30	0,43	0,040	0,070	1,75	1,98E-04
S3	0,32	0,48	0,020	0,060	3,00	9,86E-05
S4	0,29	0,40	0,018	0,043	2,43	3,01E-05
S5	0,30	0,43	0,020	0,060	3,00	5,84E-05
S6	0,31	0,43	0,024	0,050	2,08	7,56E-05
S7	0,31	0,45	0,023	0,060	2,61	8,87E-05
S8	0,27	0,36	0,025	0,058	2,32	3,86E-05
S9	0,20	0,35	0,020	0,048	2,38	2,08E-05
S10	0,26	0,35	0,029	0,050	1,72	3,80E-05
S11	0,23	0,30	0,020	0,051	2,55	1,02E-05
S12	0,28	0,39	0,021	0,050	2,38	3,77E-05
S13	0,29	0,41	0,021	0,052	2,48	4,72E-05
S14	0,30	0,43	0,023	0,055	2,39	7,16E-05
S15	0,30	0,43	0,021	0,050	2,38	5,96E-05
S16	0,26	0,40	0,021	0,050	2,40	4,24E-05
S17	0,27	0,50	0,029	0,050	1,72	2,10E-04
S18	0,34	0,52	0,029	0,054	1,86	2,58E-04
S19	0,36	0,57	0,030	0,060	2,03	4,22E-04
S20	0,31	0,44	0,028	0,060	2,14	1,14E-04
S21	0,31	0,44	0,039	0,070	1,79	2,17E-04
S22	0,25	0,30	0,030	0,065	2,17	2,18E-05
S23	0,26	0,60	0,030	0,060	2,00	5,51E-04
S24	0,38	0,70	0,060	0,100	1,67	4,22E-03
S25	0,39	0,54	0,058	0,090	1,55	1,16E-03
S26	0,30	0,35	0,050	0,100	2,00	1,23E-04
S27	0,37	0,58	0,057	0,090	1,58	1,60E-03
S28	0,35	0,50	0,050	0,080	1,60	6,09E-04
S29	0,42	0,70	0,050	0,100	2,00	3,11E-03
S30	0,36	0,56	0,030	0,067	2,23	4,15E-04
S31	0,42	0,73	0,021	0,060	2,86	7,34E-04
S32	0,42	0,70	0,050	0,080	1,60	2,89E-03
S33	0,36	0,56	0,040	0,077	1,93	7,17E-04
S34	0,39	0,64	0,050	0,093	1,86	2,00E-03
S35	0,40	0,67	0,050	0,100	2,00	2,49E-03
S36	0,26	0,34	0,025	0,040	1,60	2,56E-05
S37	0,31	0,46	0,022	0,059	2,68	9,13E-05
S38	0,31	0,45	0,020	0,041	2,05	6,19E-05
S39	0,33	0,49	0,021	0,055	2,62	1,10E-04
S40	0,35	0,54	0,022	0,061	2,77	2,10E-04
S41	0,32	0,47	0,025	0,060	2,45	1,33E-04
S42	0,31	0,44	0,023	0,055	2,39	8,10E-05
S43	0,27	0,37	0,035	0,075	2,14	7,98E-05
S44	0,30	0,40	0,020	0,050	2,50	3,97E-05
S45	0,35	0,50	0,019	0,050	2,63	1,04E-04
S46	0,32	0,48	0,035	0,085	2,43	2,82E-04
S47	0,30	0,43	0,029	0,039	1,33	9,35E-05
S48	0,29	0,41	0,029	0,041	1,41	7,79E-05
S49	0,29	0,41	0,023	0,055	2,39	5,84E-05
S50	0,29	0,42	0,024	0,056	2,33	6,75E-05
S51	0,26	0,35	0,060	0,100	1,67	1,62E-04

The porosities are between 0.20 and 0.45. The uniformity coefficients calculated using the diameters D10 and D60 are between 1 and 3. The predicted hydraulic conductivities are compared to those measured in situ by the method of double rings infiltrability in Figure 3.

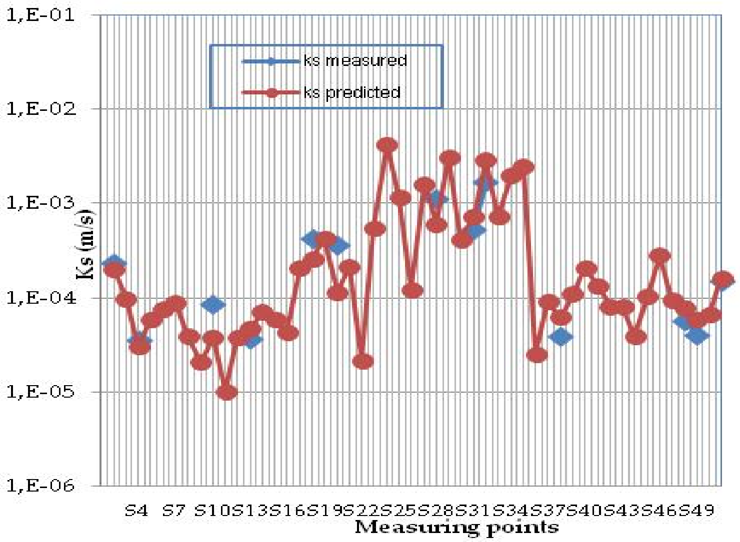

Fig. 3: Comparison of hydraulic conductivities (ks) predicted and measured

The hydraulic conductivities are between 10^{-2} and 10^{-5} m/s. Ks values measured are close to those predicted.

3.2 Water Retention Curve (WRC)

The volumetric water content of soil samples in the six wells according to sampling depths are compared with each other in Figure 4.

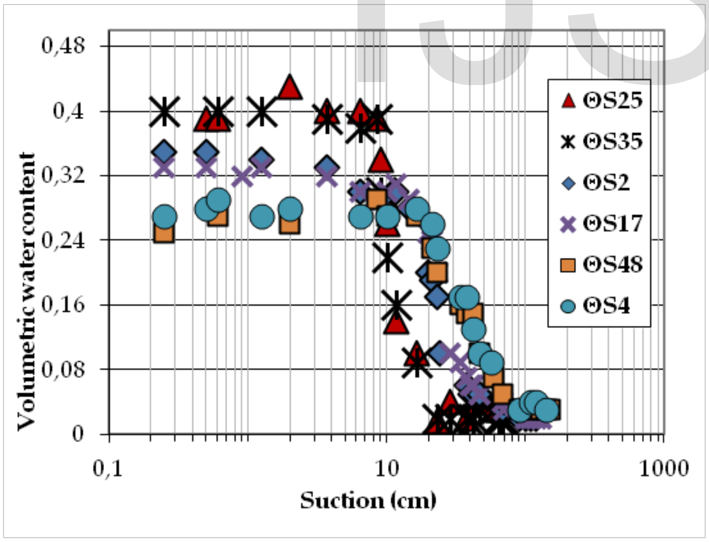

Fig. 4: Water content of soils in six wells

Three groups can be observed in the evolution of the volumetric water content of soils in the six wells. Group 1 is represented by sampling points S48 and S4, the group 2 by sampling points S2 and S17 and the group 3 represented by soil sampling S35 and S25.

The water retention curves of the three groups are predicted by the Kovac's modified model and compared to the experimental water content measured in Fig. 5.

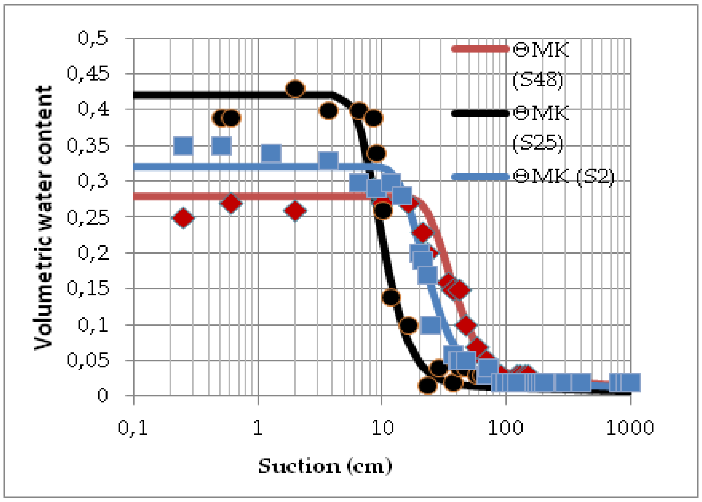

Fig. 5: Comparison of predicted water retention curves and the experimental points of water content for the three groups of soil

The maximum water content of the soil is observed in groundwater. It decreases from the groundwater to the surface. The saturated zone above the water table is less important at sampling point S25. It is more than 50 cm at points S48 and S2. This value corresponds to the capillary zone above the water table.

The suction value from which the soil starts to desaturate is the air entry value (AEV).The AEV (ψa) and empirical parameters (λ, η) of the three types of soil are determined and presented in Table 2.

TABL. 2: AEV AND EMPIRICAL PARAMETERS OF THREE TYPES OF SOIL

	λ	η	ψa
S25	0,07	2,21	5
S2	0,008	2,021	12
S48	0,004	2,012	20

3.4 Unsaturated hydraulic conductivity

These parameters are used to build the curves of unsaturated hydraulic conductivity as a function of depth in Figure 6.

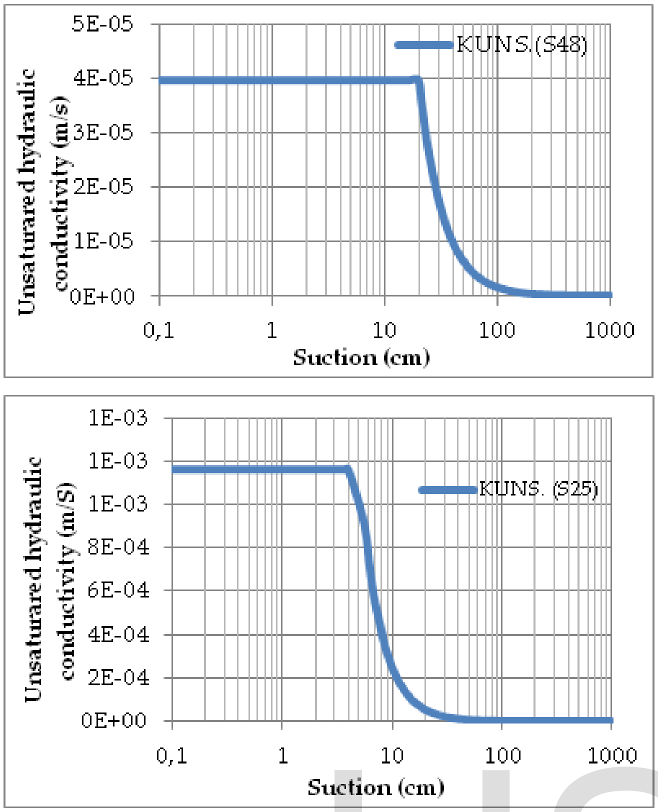

Fig.6. Predicted unsaturated hydraulic conductivities as a function of suction for the three types of soil

4. DISCUSSION

The porosities of the soil material of the Quaternary aquifer measured range from 0.20 to 0.45. These porosity values correspond to those of coarse, medium and fine sands on the scale of values defined by [29] and [30]. These sands were deposited along the West African coast during the last transgression and regression episodes dating from Quaternary [31]. These deposits of sand form the éburneo-nigerian basin which extends till Nigeria [32].

The calculated void ratio values (e) vary between 0.3 and 0.7 and the uniformity coefficients Cu of soils range from 1 to 3. These values are close to the conditions ($0.35 \leq e \leq 1.26$ and $1 \leq Cu \leq 227$) observed by [21] for the prediction of saturated hydraulic conductivity by the model of Kozeny Carman in granular soils. The predicted values of hydraulic conductivity are close to those measured in situ by the method of double rings infiltrability. These values are between 10^{-2} and 10^{-5} m/s and are close to those found by [31] on the same site. These are coarse sands ($Ks \geq 10^{-3}$ m/s), medium sands (10^{-4} m/s $\leq Ks < 10^{-3}$ m/s) and fine sands ($Ks < 10^{-4}$ m/s). These hydraulic conductivities are favorable to water and pollutants infiltration. The groundwater is exposed to continuous anthropogenic pollution already studied by [7].

The spatial distribution of these three types of sand on the entire aquifer is the fact of the sea winds. The fine sands are transported to the northern part of the aquifer by these sea winds. While the coarse sands are concentrated in the southern part [33].

The study of the water retention curve (WRC) of the three types of sand shows that the coarse sands represented by the sampling points S25 and S35 begin to desaturate around 5 cm. While the medium sands represented by S17 and S2 points and fine sands represented by the S48 and S4 points begin to desaturate respectively around 12 and 20 cm. These values are the air entry values of these three types of sand. The air entry values are close to those obtained by [22] and [34] for the same soil types. This parameter is controlled by the presence of fine particles in the granular soil. The more the particles are finer, the more the soils have the capacity to retain water when suction increases [35], [36].

The WRC show that saturated area above the water table is low in the coarse sands (10 to 20 cm) and it can reach 70 cm in fine sands. The water rises by capillarity in the soil material above the dynamic level. This zone where the water rises by capillarity varies between 10 and 20 cm for the coarse sands and can reach 70 cm in the fine sands. When the water table is at 1 m to the surface, permanent moisture is created in fine sands zone. These are high-risk areas for housing and infrastructure construction [37]. The WRC and hydraulic conductivities predicted were used to build the unsaturated hydraulic conductivity curves. The unsaturated hydraulic conductivities predicted are close to those determined by others authors [38].

5. CONCLUSION

The study of the Quaternary aquifer of Abidjan has been done through the determination of hydrodynamic properties (porosity, saturated and unsaturated hydraulic conductivity and water retention curve). These hydrodynamic properties were measured and predicted.

The measured porosity of 51 points throughout the site was between 0.25 and 0.45. These were coarse, medium and fine sands. These sands were deposited during the transgression and regression periods dated from Quaternary. The saturated hydraulic conductivities measured and predicted were between 10^{-2} and 10^{-5}m/s. These high hydraulic conductivities make the quaternary aquifer vulnerable to anthropogenic pollution.

The study of water retention curve revealed important wet fringe above the water table in parts of the aquifer. This was mainly the case of areas where there were fine sands and medium sands. This fringe could reach 70 cm in the case of fine sand. Permanent moisture is created in these areas where the dynamic level of water is less than 1 m to surface. These zones are risky areas for housing and infrastructure construction.

These studies showed that the methods of Kozeny Carman, of Kovac's and Brooks and Corey tested can be used to predict the saturated and unsaturated hydraulic conductivities of the sands of the Quaternary aquifer of Abidjan.

This study presents a new approach for aquifers study. This approach is based on the use of physical parameter of soil easy to measure to predict hydrodynamic parameters. It can be extended to the study of other aquifers in particular those bordering throughout West Africa in a context where in situ measurements are difficult to perform. The hydrodynamic properties obtained are useful for the development of pollutant transfer model. This allows understanding the functioning of quaternary aquifers.

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