



# Comparative Analysis for Estimating Hydraulic Conductivity Values to Improve the Estimation of Groundwater Recharge in Yaoundé-Cameroon

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## Authors' contributions

*This work was carried out in collaboration between all authors. Author AFT designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors WF, JNN and LSN managed the literature searches and improved the discussions. All authors read and approved the final manuscript.*

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## ABSTRACT

Climate change will deeply affect the precipitation and evapotranspiration around the world. The sustainability of groundwater resources is crucial for regional and local communities, which is intimately tied to the changing recharge rate. To accurately assess the recharge rate, different methods were used to estimate hydraulic conductivity of an unconfined aquifer in this study. Particle size method with four empirical formulae, together with in-situ aquifer tests and the inverse modelling techniques were integrated to evaluate their potential for the determination of hydraulic conductivity of unconsolidated aquifer materials in order to improve groundwater recharge estimation. Results showed a wide disparity between the granulometric estimates of the hydraulic conductivity and the in-situ and modelling techniques. Slug test values range from  $5.13 \times 10^{-6}$  m/s to  $4.96 \times 10^{-5}$  m/s whereas the infiltration test (Porchet method) results vary from  $1.91 \times 10^{-7}$  m/s to  $1.16 \times 10^{-6}$  m/s. The simulated hydraulic conductivity values range from  $2.54 \times 10^{-7}$  m/s to  $6.36 \times 10^{-7}$  m/s, with a decreasing trend in the northeast-southwest (NE-SW) direction.

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The infiltration method appeared to be better than the granulometric one in the estimation of the vertical hydraulic conductivity within the unsaturated zone of porous formations. This study also pointed out that within an anisotropic formation, the hydraulic conductivity ratio ( $K_v/K_h$ ) should not always be taken as equal to 10. Specific tests should be implemented to access this value in a given aquifer. The inverse modelling results showed the net recharge values varying from 68.5 mm/yr to 180 mm/yr. The modelling technique appears to be consistent with the in-situ estimates. Therefore, the application of groundwater modelling tool in this study has shown excellent promise for characterizing the spatial distribution of hydraulic conductivity and net recharge values within the targeted aquifer system.

*Keywords: Grain size; hydraulic conductivity; slug test; inverse modelling; Yaounde.*

## 1. INTRODUCTION

Changes in climatological patterns can be expected to influence hydrological cycles globally. Implications of climate change for fresh groundwater resources have been well recognized worldwide [1]. To understand more about the relationship of climate-change and hydrologic and aquifer processes, different techniques have to be applied to determine the hydraulic conductivity values of aquifers. They include but are not limited to field methods (pumping test, slug test and tracer test), laboratory hydraulic conductivity tests, and estimation based on empirical formulae [2]. Even though accurate estimation of hydraulic conductivity may be conducted in the field environment, the lack of precise knowledge of aquifer geometry and hydraulic boundaries sometimes limit its application potential [3].

Hydraulic conductivity can be deeply influenced by grain size distribution. Grain-size analysis is the sedimentological technique to characterise and interpret sediments and sedimentary rocks. The grain-size analysis method is comparably less expensive and do not depend on the geometry and hydraulic boundaries of the aquifer. Numerous investigators have studied this relationship and several formulae have resulted based on relevant experimental work [4]. However, Landon et al. [5] reported that grain-size analyses are generally less reliable technique due to a distortion of the texture of the in-situ medium. In Cameroon, granulometric analyses have been carried out at various locations in Yaounde to examine the physical and hydrodynamic characteristics of the shallow aquifer. Results indicate hydraulic conductivity values varying from  $8.17 \times 10^{-7}$  m/s to  $2.26 \times 10^{-5}$  m/s [6,7,8].

Different field tests may be carried out to achieve the estimation of hydraulic conductivity too. The principle of the slug test consists of analyzing the rate of water level fluctuation in well after a certain volume ("slug") of water is suddenly removed/added from/into the well. Emerging/submerging a cylinder in the well creates a cone of depression/pression, which corresponds to pumping/injection test and which makes it possible to determine the horizontal distribution of the hydraulic conductivity of an anisotropic formation [9], [10], [11] and [12]. Mace [13] presented a method, specifically designed for interpreting slug tests in large-diameter wells and showed that values obtained are comparable to those determined by numerical methods. Successful case studies of slug test experiments can be found in [14] in South Korea; [10] in Nigeria, [15] in India and [16] in Denmark. On the other hand, the infiltration test (Porchet method) is based on observing the rate of draw down of the water level below which the infiltration occurs, after the application of water has been stopped. Granulometric techniques have already been applied in Yaounde to determine the aquifer

hydrodynamic properties with acceptable result albeit the slug test and the modelling techniques are still implementable with the aim to improve the results.

The practice of aquifer permeability tests can be complementary to practical numerical techniques (models) that take into account the three-dimensional interplay of flow, stress, and strain in aquifers [17]. However, there is a growing trend for the determination of regional permeability of aquifer through numerical simulation methods [18], [19] and [20]. As numerical models become more sophisticated and as more data become available, such simulation methods are likely to have increasing applications [17]. The Visual Modflow code is then used in this study and run in direct and inverse mode. Inverse modelling is an important and necessary step in hydrogeological studies because it helps to improve parameter estimation [21]. Given that changes in climatological patterns within the watershed were expected to influence hydrological cycles locally, the objectives of this paper is therefore to (i) compare different methods for the determination of the best estimates of hydraulic conductivity of unconsolidated soil (granulometric, porchet test) and shallow aquifer (slug test) at a specific location; and (ii) characterize spatial distribution of aquifer hydraulic conductivity and recharge to aquifer (modelling).

## **2. MATERIALS AND METHODS**

### **2.1 Study Area**

The city of Yaounde is the political capital of Cameroon and is located about 250 km from the Atlantic coast and the edge of the Congolese forest and covers an area of about 300 km<sup>2</sup>. It lies between latitudes 03° 45' N and 04° 00' N and longitudes 11° 20' E and 11° 40' E. It is drained by a dense dendritic rivers network (Fig. 1). The study area falls in a region of equatorial climate with four distinct seasons. An abundant precipitation of 1600 mm/y, an average temperature of 24°C and an evaporation of 800 mm /y characterize this climate. The soils are predominately ferric and lateritic. The weathered zone is typically 15 to 20 m thick clay and acidic (pH <5.5). The slopes are steep in the upland, giving rise to rapid flow of surface runoff, and thus sustaining the development of many wetlands in the lowlands.

### **2.2 Aquifer System**

The shallow unconfined aquifer system of interest in this study generally consists of two topographical areas which are interconnected; the lateritic aquifer in the elevated zones and in the lower zones. Within the elevated zones, the aquifer is sometimes fissured and is overlain by a thick lateritic unconfined formation. The depth of the monitoring wells varies from 14.2 to 27.2 m below land surface (b.l.s). The aquifer is one of the good sources of water in the area in terms of water availability and quality. This zone generally constitutes the principal recharge area for the aquifers in the lower zones. Within these lower zones, the water table is shallow. The depth of the monitoring wells varies from 4.7 to 14.8 m b.l.s. The population exploits it through shallow wells. The aquifer is not highly influenced by water-level fluctuations like in the elevated zones.

### **2.3 Grain Size Analysis**

Empirical formulae based on grain-size distribution characteristics have been used to estimate the hydraulic conductivity (Table 1). To support the calculation, soil samples were taken generally at 50 cm depth for granulometric analyses. Sample S7 was collected at 8 m

depth. Particle size distribution parameters were determined through conventional sieve method, consisted by a set of eight sieves with a mesh sizes from 0.28 to 5.6 mm for coarser particles at the laboratory of “Geology of Engineers” of the University of Yaoundé I, and hydrometer method for finer particle (diameter less than 2 mm) at the “International Institute for Tropical Agriculture” (IITA) soil laboratory of Yaounde.

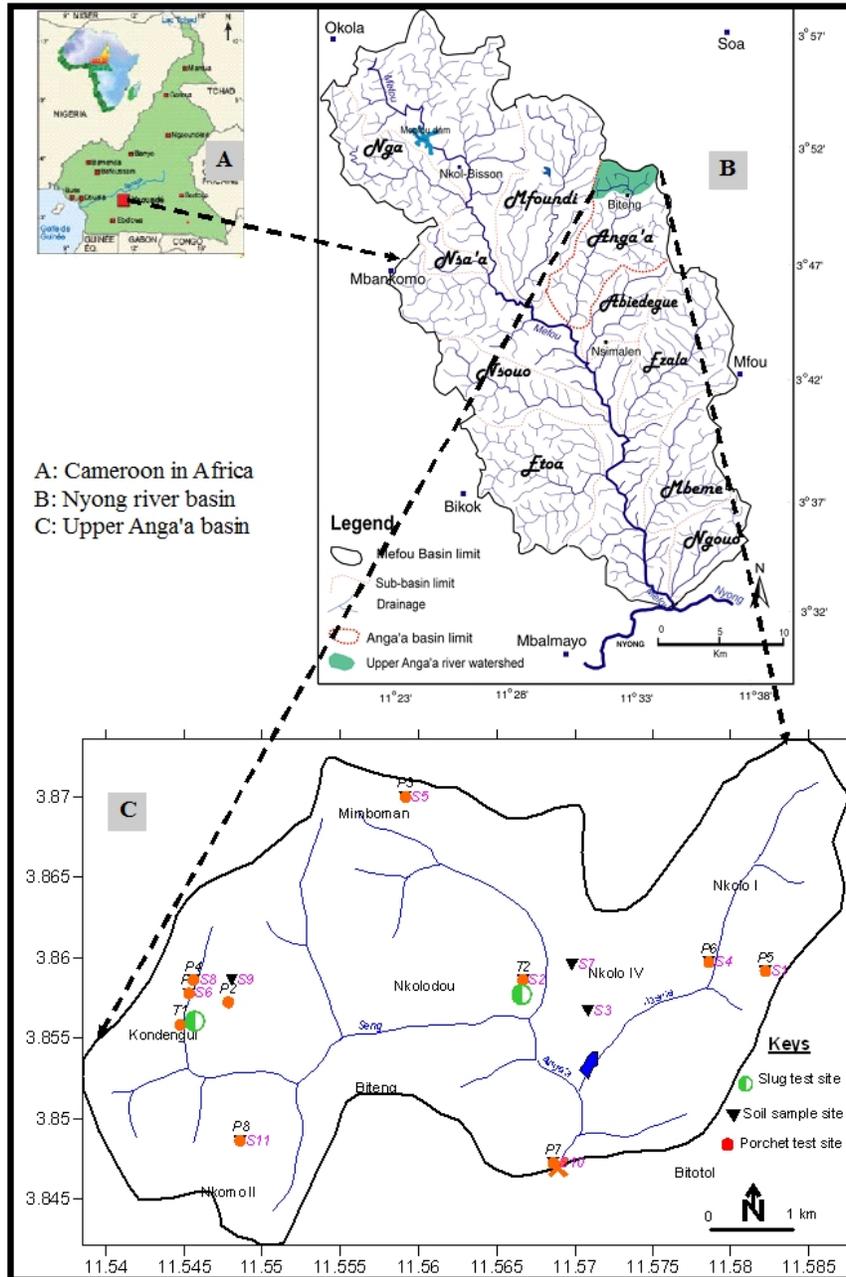


Fig. 1. Study area within the Nyong river basin and aquifer test sites

**Table 1. Empirical formulae based on grain-size distribution characteristics used to estimate hydraulic conductivity K (m/s)**

Method	Formula	Validity	Application	References
<b>Hazen</b>	$K = \frac{g}{\nu} \times 6 \times 10^{-4} [1 + 10(n - 0.26)] d_{10}^2$	The sediment has a uniformity coefficient less than 5 and effective grain size between 0.1 and 3mm.	Determination of K of uniformly graded sand but also useful for fine sand to gravel range.	[22]
<b>Breyer</b>	$K = \frac{g}{\nu} \times 6 \times 10^{-4} \log \frac{500}{U} d_{10}^2$	poorly sorted grains with uniformity coefficient between 1 and 20, and effective grain size between 0.06 mm and 0.6 mm.	Does not consider porosity and therefore, porosity function takes on value 1.	[23]
<b>Kozeny-Carman</b>	$K = \frac{g}{\nu} \times 8.3 \times 10^{-3} \left[ \frac{n^3}{(1-n)^2} \right] d_{10}^2$	It is not appropriate for either soil with effective size above 3 mm or for clayey soils (Carrier 2003).	One of the most widely accepted and used derivations of permeability as a function of the characteristics of the soil medium	[24]
<b>U.S. Bureau of Reclamation (USBR)</b>	$K = \frac{g}{\nu} \times 4.8 \times 10^{-4} d_{20}^{0.3} \times d_{20}^2$	most suitable for medium-grain sand with uniformity coefficient less than 5 (Cheng and Chen, 2007)	calculates K from the effective grain size ( $d_{20}$ ), and does not depend on porosity;	[25]

*K: hydraulic conductivity; g: acceleration of gravity;  $\nu$ : kinematic viscosity of the water and  $d_e$ : effective grain diameter. The kinematic viscosity ( $\nu$ ) is related to dynamic viscosity ( $\mu$ ) and the fluid (water) density ( $\rho$ ) as follows:  $\nu = \mu/\rho$ ,  $n = 0.255(1 + 0.83^U)$*

## 2.4 Slug Tests

The bailer tests were conducted at two sites in the Anga'a basin between the 16<sup>th</sup> and 17<sup>th</sup> August, 2009. The equipment used was made of an electric pump, a stop watch and an electric water level. In theory, the calculation of the hydraulic conductivity of the aquifer in the vicinity of the well is given by the equation of Bouwer and Rice [9].

### **2.4.1 Site t1: frontière**

The chosen well is situated near the river Anga'a at a distance of 21 meters (Fig. 1). The well is located on lateritic soil with high density of nodules. It is used by the residents of the neighbouring concessions for cleaning and laundry. It has a total depth of 3.40 m. The test lasted 5h 40 min. The discharge of well was done using a pump outputting  $Q = 4$  l/s. The discharge lasted 5 minutes, thus satisfying the test conditions [13], [10], and [26]. The rise (recovery) lasted 5h 35 min, time to get 1/10th of the pumped water.

### **2.4.2 Site t2: Emombo sous-avocatier**

The well is located in the valley, near a swamp, under a large avocado tree (Fig. 1). Resurgences are located in its vicinity, testifying the saturation and especially the high hydraulic conductivity of the soil. The well is used by the residents of the neighbouring households for cleaning and laundry. It has a total depth of 2.20 m. The discharge of the well was made with the same pump and also lasted 5 minutes. The test lasted 2 h, with 1h 55 min for the rise that was covered at 100% (full recovery). Table 2 presents the technical characteristics of the above mentioned wells. The tests took place in the wet season, in clear weather and no rain. These data were processed manually and with the help of the computer software *Aquifer Test 3.1* by the Hvorslev method.

In addition, vertical hydraulic gradient field test was performed on March 2009 in the Anga'a river, at about 200 m to the basin outlet, at the beginning of the raining season. The objective of the test was to quantify the vertical hydraulic gradient. This measurement method requires only relatively simple equipment. A mini-piezometer mainly composed of an open-ended pipe with the bottom tip fitted with slotted screen to allow the inflow/outflow of water. The strainer was pressed at a known depth in the river bed for measuring the difference between the water level inside the mini-piezometer and the river water level with an electric sensor.

**Table 2. Technical characteristics of the tested wells**

Site	H (m)	L (m)	D (m)	$r_c$ (m)	$r_w$ (m)
Frontière	3.22	0.82	-	0.5	0.55
Emombo	1.27	1.2	-	0.45	0.50

*H is the initial height of water inside the well; L is the length of the well screen or perforated zone of well; D is the aquifer thickness;  $r_c$  is the casing/well radius; and  $r_w$  is the well screen radius or radius of screen plus thickness of the gravel envelope or developed zone.*

## **2.5 Infiltration Tests**

The infiltration tests (Porchet method) were conducted at eight sites (S1,...,S8) in the Anga'a basin between July 24 and September 06, 2009 (Fig. 1). The sites were judiciously selected to have good distribution in the basin. A hand auger of 8 cm in diameter was used to drill holes ranging from 50 cm to 1 m deep in humus; laterite and clay horizons. The depth of the holes was usually limited by soil resistance to the progression of the auger. To maintain the natural condition of the test sites, the sides and bottoms of the holes were neither brushed nor pickled. The hole was filled up with water until saturation. The measurement started only after sufficient water has been applied to ensure the saturation of a large enough part of the soil around and below the place of measurement. Using a clock and a ruler, measurement of the speed at which the water went down was performed. The experience ends when the

measuring speed becomes almost constant. The Darcy's law was used to calculate the hydraulic conductivity. The infiltration surface was constituted by the sides and bottom of the hole.

## 2.6 Recharge Data for Comparison

A study of environmental Chloride, groundwater balance and the water table fluctuation methods were carried out in order to estimate their relative values for measuring average groundwater recharge under a humid climatic environment with a relatively shallow water table [27]. Effective specific yield of 0.08 was obtained for the study area. The hybrid water fluctuation method gave recharge values varying from 22 mm/y to 188 mm/y with an average value of 87.14 mm/y at the basin scale, which represents 5.7% of the annual rainfall (Fig. 2).

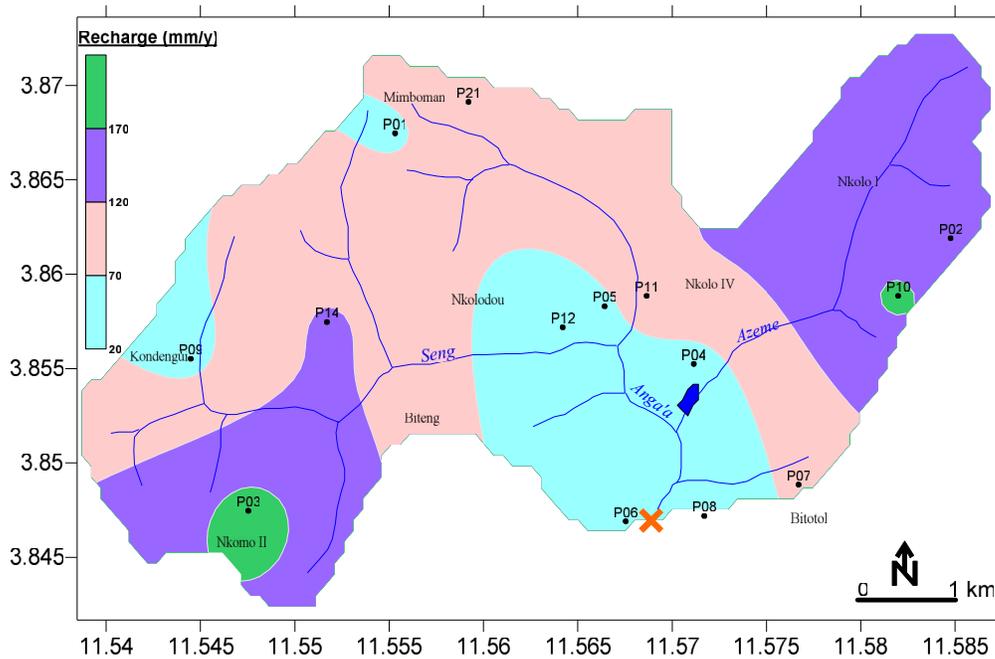


Fig. 2. Areal distribution of groundwater recharge at the basin scale based on the hybrid –water fluctuation method

## 2.7 Forward and Inverse Groundwater Flow Modelling

Visual MODFLOW, which is implemented in this paper is the most complete and easy-to-use modelling environment for practical applications in three-dimensional groundwater flow and contaminant transport simulations [28]. It uses finite-difference approximation with block centered formulation to solve groundwater flow equation. It utilizes iterative methods to obtain the solution to the system of finite-difference equations for each time step [29]. Visual MODFLOW 4.2 software was used to determine the distribution of piezometric head and simulate groundwater flow. The model conceptualisation involved: (1) defining a simulation domain and the hydrogeological layers; (2) dividing this domain into zones, each of which possesses a unique set of hydraulic properties; (3) defining the outside boundary conditions along the six sides of the model domain; (4) determining the internal boundary conditions such as rivers, wells, recharge, evapotranspiration, drain and head dependant fluxes, which

are also called stresses; and (5) collecting values of measured hydraulic head [11]. A general form of the equation describing the transient flow of a compressible fluid in a non-homogeneous anisotropic aquifer may be derived by combining Darcy's law with the continuity equation. The three-dimensional movement of ground water of constant density through porous earth material may be described by the partial-differential equation:

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) + W = S_s \frac{\partial h}{\partial t} \quad (1)$$

Where,

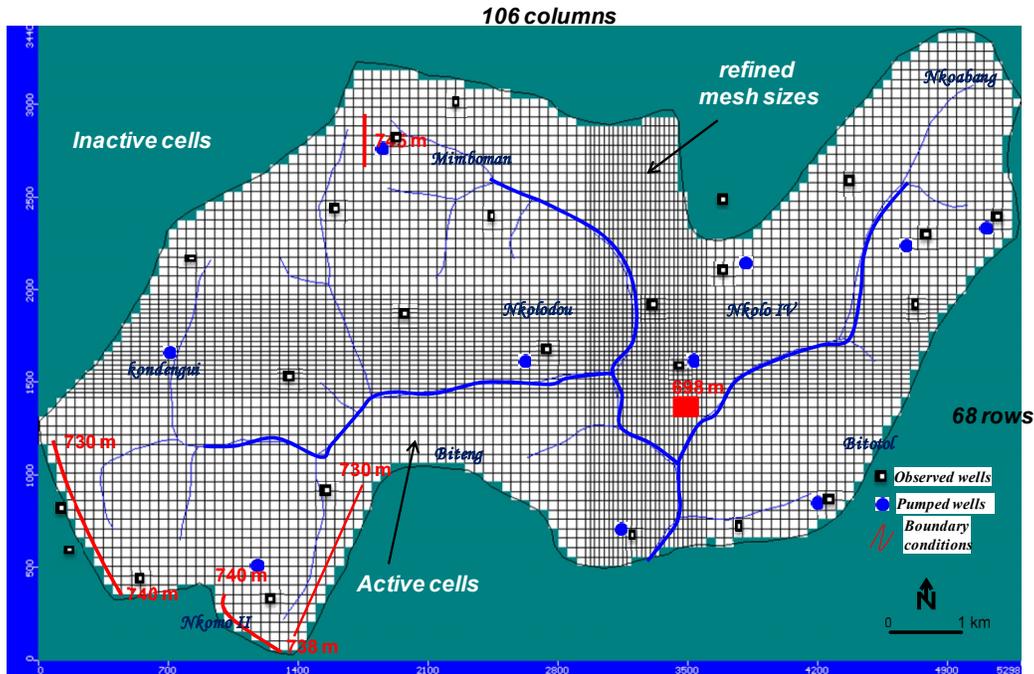
$K_{xx}$ ,  $K_{yy}$ , and  $K_{zz}$  are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity [L/T];  $h$  is the potentiometric head [L];  $W$  is a volumetric flux per unit volume representing sources and/or sinks of water, with  $W < 0.0$  for flow out of the ground-water system, and  $W > 0.0$  for flow into the system [ $T^{-1}$ ];  $S_s$  is the specific storage of the porous material [ $L^{-1}$ ]; and  $t$  is time [T].

Equation 1, together with specification of flow and/or head conditions at the boundaries of an aquifer system and specification of initial-head conditions, constitutes a mathematical representation of a groundwater flow system [29]. Detailed descriptions of the model configuration have been made earlier by Takounjou et al. [30]. A brief description in regard to this study is made hereunder. The simulated model domain of the Anga'a river watershed consists of 106 columns and 68 rows. The modelled area is discretized into two layers; the first layer is unconfined while the second layer is assumed to be semi-confined [30]. The top layer mostly consists of 2 - 18 m top soil clay/sandy weathered zone underlain by 15 - 25 m fractured zone. Cells over the basin are 50m X 50m, with more than 4370 active cells (Fig. 3). The model grids were refined by 25m X 25m around the Nkolo IV fish pond and river outlet areas to get more detailed simulation result. As regards boundary conditions, the outflow from groundwater flow model was estimated in term of few constant head nodes and Anga'a River was simulated with river package in the Visual MODFLOW. The groundwater recharge distribution obtained previously was simulated on the top of the aquifer by deploying the recharge package. Natural vegetation may sustain with an average evapotranspiration of 70 mm/yr and the same has been assigned to all cells in the watershed. Even though groundwater is the only available resource for drinking water in the area, just few pumping wells can be found in the watershed. People are depending on traditional dug well for household laundry. Drinking water comes from few traditional sealed dug wells with hand pump in the rural area, and piped water network in the urban area. Vegetable are grown in the swampy zone during pre-monsoon and Anga'a River is used to sprinkle the crops. Groundwater pumping rates was assumed to be varying from 10 m<sup>3</sup>/day to 18 m<sup>3</sup>/day. The groundwater flow model was constructed for computation of hydraulic head distribution. Groundwater processes within the watershed was simulated for 10 years with stress period of 140 days. For the simulation, 16 observation wells and 9 springs were included on the calculated versus observed heads graph. The groundwater levels measured during February 2008 were used as initial water level configuration for the Anga'a watershed groundwater flow model. The groundwater flow model has converged after 170 iterations.

The following information was used during conceptualisation of the flow regime:

- The Anga'a river is a perennial stream and is influent throughout its course.
- The Nkolo IV fish pond(Lake) is assumed to be maintaining a level and is sustained through base flow from the river;

- The Diriclet boundary condition is applied in the northern part of the watershed, at *Mimboman*, which allows entry of lateral flow;
- The same conditions are applied in the western and south-western areas, at *Biteng*; and in the south-eastern area at *Bitotol* ;
- Groundwater leaves the watershed at various places: in the southern area through Anga'a river, and in the south-west and north-east;
- Groundwater recharge due to rainfall enters the aquifer from the top layer;
- Springs discharge are considered as groundwater withdrawal through stream-aquifer interaction.



**Fig. 3. Spatial discretization and boundary conditions of the watershed highlighting values of constant head (in red), observed wells (black squares) and pumping wells (in blue)**

Moreover, the inverse modelling refers to the process of gathering information on the model and/or its parameters from (historical) measurements of what is being modelled [31]. Several inversion techniques were developed during the last decades. PEST (which is an acronym for Parameter ESTimation) is one of the model-independent parameter optimizer and was used to accomplish this task. PEST is widely used for nonlinear parameter estimation and optimization modelling. More information regarding PEST can be found in [32]; while the importance of the inverse modelling technique in the groundwater flow domain is well documented in [33,34]. Once the model outputted the piezometric head distribution, the model was run in inverse mode with the help of PEST code in order to refine the recharge distribution, considering all the parameters known except the recharge. The model calibration by systematic parameter variation was used with the goal of matching the observation data as closely as possible. A trial and error calibration technique was used. The flow model was calibrated by adjusting several parameters (hydraulic conductivity K, recharge, river stage and aquifer thickness) within a narrow range of values until the best fit

was obtained between the observed heads and simulated heads [35]. The accuracy of the computed groundwater levels was judged by a mean error, mean absolute error and root mean square error of computed values for points on the graph [36]. The objectives function was made of measured head data. The 16 observation wells were divided in three groups and the influence of each group on the objective function was controlled separately.

### **3. RESULTS AND DISCUSSION**

#### **3.1 Aquifer Hydraulic Properties**

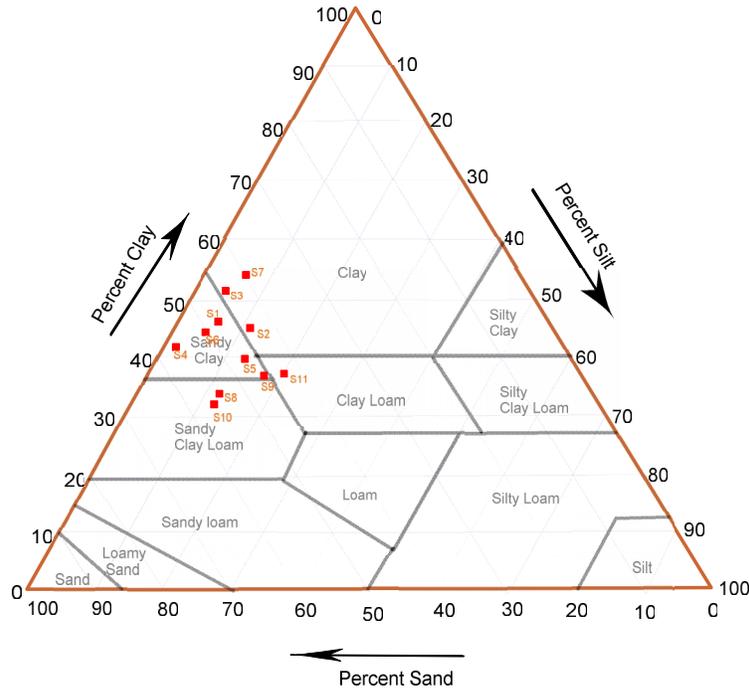
Hydrometric analysis samples allowed the classification of the Anga'a soil according to the US soil conservation standards [37] (Fig. 4). It is observable that all the samples fall within the clay-enriched area, with three samples (S2, S3 and S7) completely clay and one sample (S11) clay-loam. This textural feature of the samples indicates small values of hydraulic conductivity (K) and hence their implication in the recharge process. Table 3 presents the soil sample analysis data of the Anga'a basin. Estimates of K were obtained for the same samples using different granulometric methods, the results are displayed in Table 4. The Hazen formula gives K estimates varying from  $9.36 \times 10^{-4}$  to  $3.55 \times 10^{-3}$  m/s with an average value of  $2.46 \times 10^{-3}$  m/s; the Kozeny formula gives K estimates varying from  $7.37 \times 10^{-4}$  to  $3.18 \times 10^{-3}$  m/s with an average value of  $1.99 \times 10^{-3}$  m/s; the Breyer formula gives K estimates varying from  $9.51 \times 10^{-4}$  to  $3.48 \times 10^{-3}$  m/s with an average value of  $2.51 \times 10^{-3}$  m/s and the USBR formula gives K estimates varying from  $9.58 \times 10^{-5}$  to  $5.21 \times 10^{-4}$  m/s with an average value of  $2.75 \times 10^{-4}$  m/s. These values appear to be falling in the domain of moderate permeable medium [38].

Slug test values for the shallow unconfined aquifer range from  $5.13 \times 10^{-6}$  m/s in Frontiere well's area to  $4.96 \times 10^{-5}$  m/s in Emombo well's neighbourhood (Fig. 5). The distribution of the hydraulic conductivity by the Porchet tests varies from  $1.91 \times 10^{-7}$  m/s at Mimboman dispensary to  $1.16 \times 10^{-6}$  m/s at the Anga'a outlet area. The average value is  $5.90 \times 10^{-7}$  m/s. The distribution of hydraulic conductivity obtained (Table 4) constitutes a preliminary estimate of the hydraulic conductivity of the lateritic weathered layer in close proximity to the wells investigated.

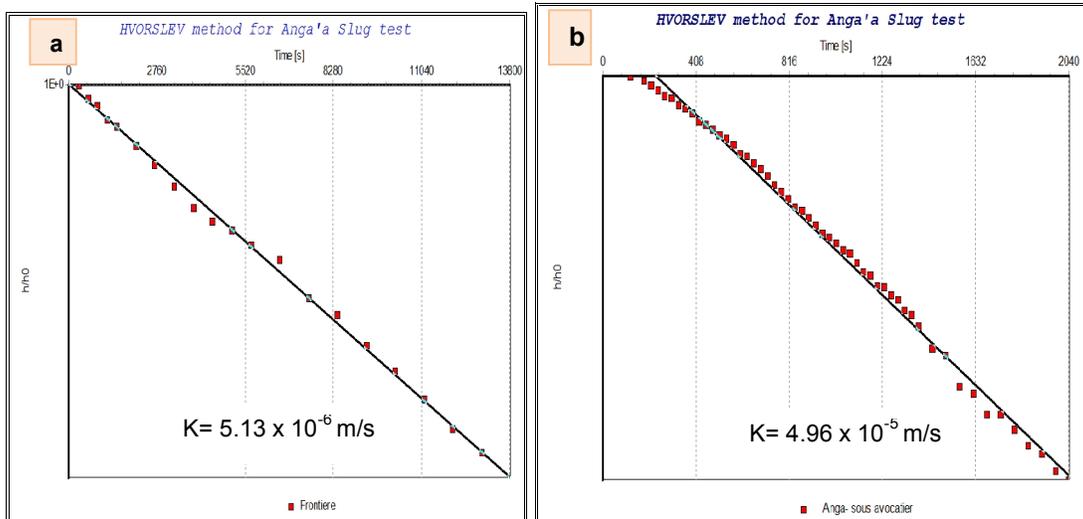
The model simulated hydraulic conductivity values for the aquifer second layer range from  $2.54 \times 10^{-7}$  to  $6.36 \times 10^{-7}$  m/s, with a decreasing trend in the northeast- southwest (NE-SW) direction. Fig. 6 displays the distribution of the simulated hydraulic conductivity values in the second layer of the aquifer.

Results show that within the top soil, the different granulometric methods used for estimating the vertical hydraulic conductivity (Kv) value are giving almost the same estimate. Hazen and Breyer formula are displaying the same hydraulic conductivity value ( $2.5 \times 10^{-3}$  m/s); the kozeny method is showing a relatively small value. Except from the USBR method that gives a K magnitude of  $10^{-4}$ , all the three other methods are presenting the same magnitude of the hydraulic conductivity value ( $10^{-3}$ ). However, these values seem to be higher compare to the textural feature of the formation mentioned above. Caution should be pay while using those methods. Within the same unsaturated zone, the infiltration method is indicating an average hydraulic conductivity value of  $5.90 \times 10^{-7}$  m/s, which is four level of magnitude smaller than the granulometric values, but seems to be in good agreement with the soil texture. The infiltration method then appears to be better.

Within the saturated zone, the average horizontal hydraulic conductivity (Kh) value estimated by the slug test method is  $2.73 \times 10^{-5}$  m/s. Putting aside the granulometric value; results are indicating the anisotropic characteristic of the aquifer. The vertical hydraulic conductivity value is hundred times smaller than the horizontal one. It should be recalled that generally in modelling studies, modeller assume  $K_h/K_v=10$ .



**Fig. 4. Soil triangle highlighting the basic soil textural classes of the Anga'a river basin**



**Fig. 5. Hydraulic conductivity values (K) estimated with the slug test method**

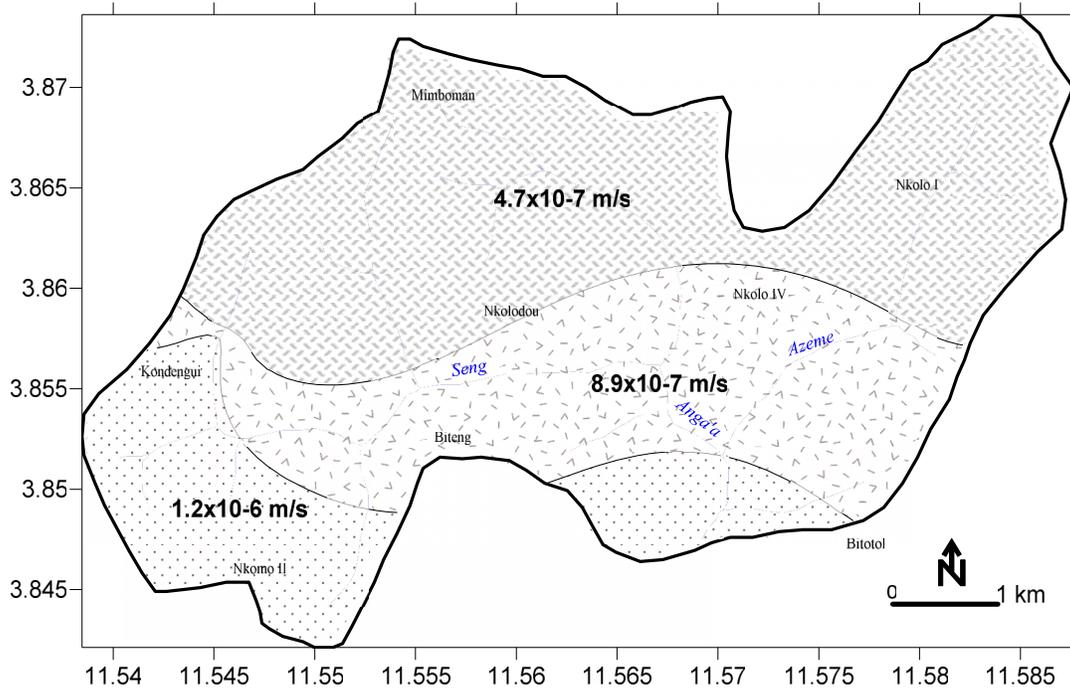
**Table 3. Results of the soil samples analyses; (a) Sedimentology & (b) Granulometric**

<b>Samples</b>	<b>S1</b>	<b>S2</b>	<b>S3</b>	<b>S4</b>	<b>S5</b>	<b>S6</b>	<b>S7</b>	<b>S8</b>	<b>S9</b>	<b>S10</b>	<b>S11</b>
<b>(a)</b> Sand (%)	47.96	44.08	43.24	54.6	48.6	49	42.52	53.6	44.6	54.6	43.24
Clay (%)	44.4	44.4	51.76	41.76	41.4	43.4	52.76	34.4	37.4	33.4	38.4
Silt (%)	7.64	11.52	5	3.64	10	7.6	4.72	12	18	12	18.36
<b>Mesh sizes (mm)</b>	<b>S1</b>	<b>S2</b>	<b>S3</b>	<b>S4</b>	<b>S5</b>	<b>S6</b>	<b>S7</b>	<b>S8</b>	<b>S9</b>	<b>S10</b>	
5.6	182.6	262.91	14.98	152.69	52.66	47	5.27	10.42	24.6	77.75	
4	60.73	24.62	11.39	23.92	22.92	25.9	11.57	9.36	40.74	33.37	
2	113.89	72.29	67.68	117.8	122	80.09	140.54	55.9	84.76	127.6	
1	90.45	112.27	205.77	120.82	197.76	160.87	213.66	115.6	132.96	317.57	
0.5	76.5	95.88	130.74	121.86	112.27	163.38	105.21	138.19	142.57	107.54	
0.4	18.15	16.03	28.69	25.25	19.89	69.2	18.5	31.16	54.46	27.11	
0.315	7.27	6.11	12.52	10.15	-	26.16	6.56	16.84	23.74	12.2	
0.28	-	-	-	-	-	6.83	-	-	6	-	
PAN	19.64	16.9	45.21	33.81	28.4	31.2	16.56	50.59	70.53	43.22	
<b>Total Mass (g)</b>	<b>569.5</b>	<b>612.93</b>	<b>519.2</b>	<b>608.37</b>	<b>559.73</b>	<b>622.38</b>	<b>519.65</b>	<b>429.2</b>	<b>594.4</b>	<b>749.39</b>	

**Table 4. Hydraulic conductivity values from different methods**

<b>Location</b>	<b>Grain size analysis</b>							<b>Hydraulics conductivities (m/s)</b>						
	<b>d10</b>	<b>d20</b>	<b>d30</b>	<b>d60</b>	<b>d90</b>	<b>U</b>	<b>n</b>	<b>Hazen</b>	<b>Kozeny</b>	<b>Breyer</b>	<b>USBR</b>	<b>Porchet</b>	<b>Slug test</b>	<b>Modelling</b>
P5, S1	0.55	0.94	1.5	4.5	-	8.18	0.31	n.a	1.56E-03	3.22E-03	5.21E-04	4.03E-07	2.54E-07	
S3	0.35	0.55	0.7	1.5	3	4.28	0.37	1.53E-03	1.29E-03	1.51E-03	1.52E-04		to	
P6, S4	0.45	0.68	0.95	2.75	-	6.11	0.34	n.a	1.50E-03	2.31E-03	2.47E-04	4.55E-07	6.36E-07	
P3, S5	0.5	0.72	1.1	1.8	5.1	3.6	0.38	3.28E-03	2.94E-03	3.19E-03	2.83E-04	1.91E-07		
S7	0.52	0.75	1.1	1.8	3.5	3.46	0.38	3.55E-03	3.18E-03	3.48E-03	3.10E-04			
P7, S10	0.48	0.76	1.2	1.8	5.5	3.75	0.38	3.02E-03	2.71E-03	2.92E-03	3.19E-04	1.16E-06		
P1, S6	0.28	0.45	0.58	1.3	3	4.64	0.36	9.36E-04	7.37E-04	9.51E-04	9.58E-05	1.96E-07		
P2												2.81E-07		
P8												1.00E-06		
T2, S2												1.03E-06	4.96E-05	
T1												-	5.13E-06	

*d10: effective grain size, n: porosity, U: uniformity coefficient, n.a: not available*



**Fig. 6. Hydraulic conductivities values in the modelled area**

### 3.2 Net Recharge from Inverse Modelling

Inverse modelling was used to refine initial recharge estimated by the hybrid water fluctuation and hydrochemistry methods [28]. The inverse model produced net recharge values varying from 68.5 mm/yr to 180 mm/yr (Fig. 7). These values are within the window of the previous values (from 22 mm/y to 188 mm/y) and are in good agreements with the hydrogeological features of the watershed. The accuracy of the computed groundwater levels can be observed in Figs. 8 and 9. Fig. 8 displays statistics about the accuracy of the computed groundwater levels. It is observable that the normalised roots mean squared error is less than 5% percent which is well within the accepted calibration accuracy of 10 percent for a medium complexity 'Impact Assessment Model' [39]. Fig. 9 shows that the model is sensitive to the hydraulic conductivity values and not to the storage and specific yield parameters. Particular caution should definitely be paid with the determination of the hydraulic conductivity because it considerably impacts on the model calibration and hence on the recharge estimation.

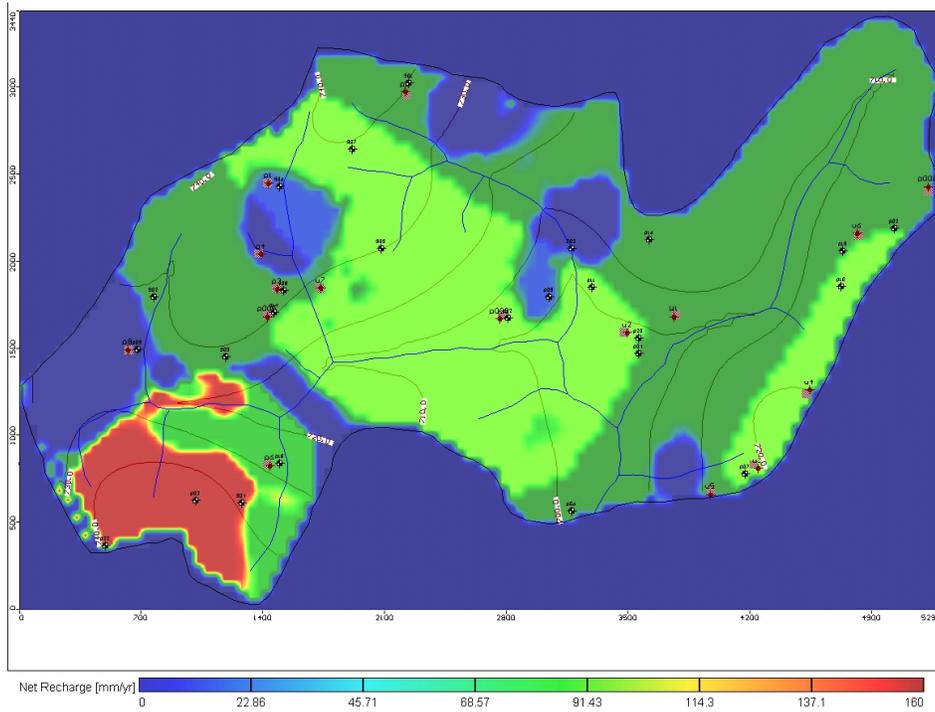


Fig. 7. Net areal recharge distributions from the inverse modeling.

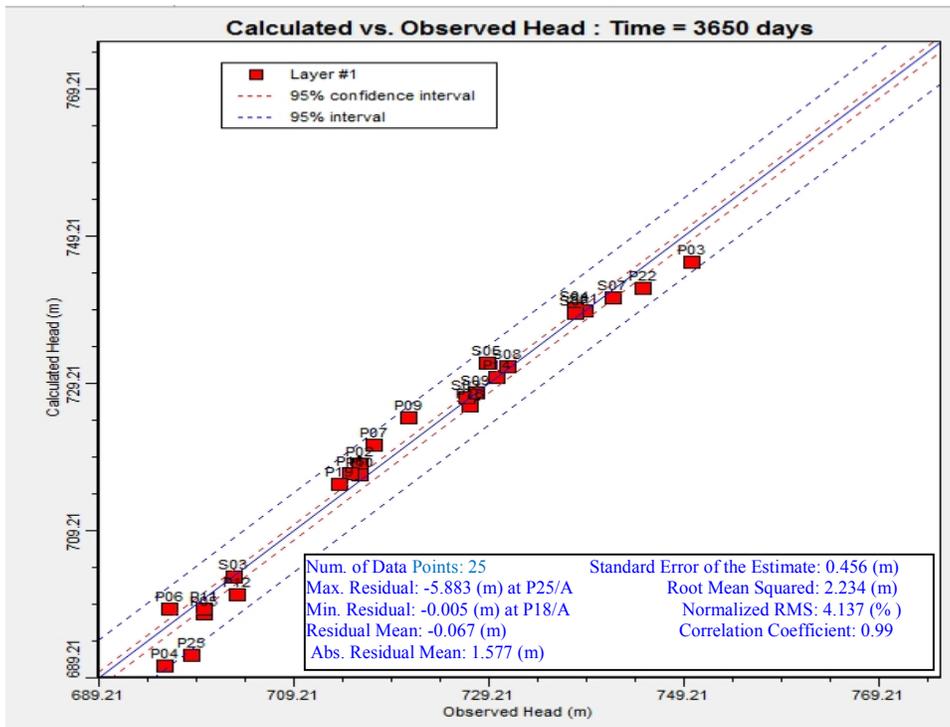
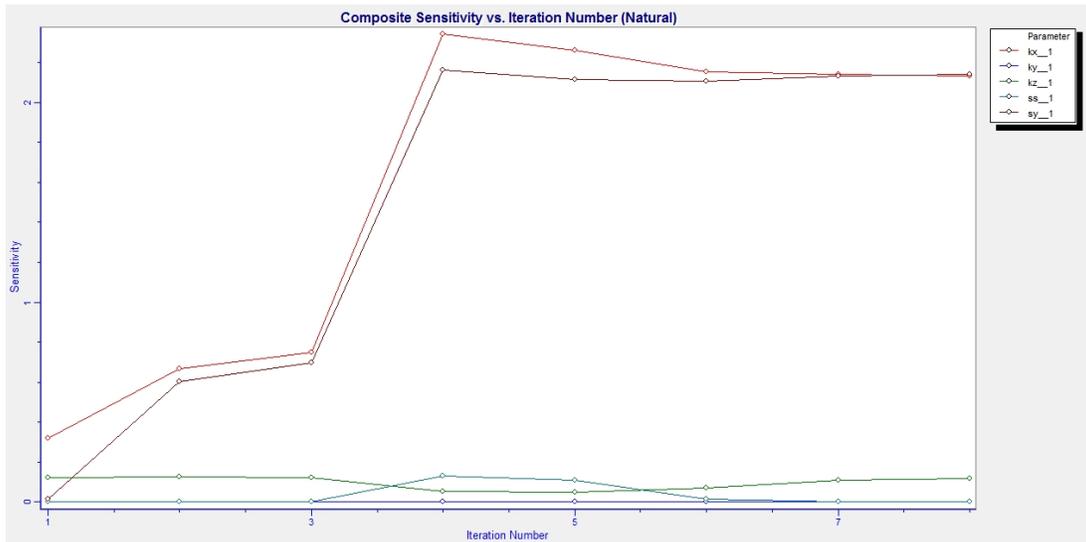


Fig. 8. Comparison of Computed vs. Observed groundwater levels in the watershed.



**Fig. 9. Composite sensitivity vs. iteration number curve.**

#### 4. DISCUSSION

Slug test values which range from  $5.13 \times 10^{-6}$  m/s in Frontiere area to  $4.96 \times 10^{-5}$  m/s in Emombo well's neighbourhood constitute preliminary estimates of the horizontal hydraulic conductivity of the lateritic layer in close proximity to the wells. In the absence of available studies on hydraulic conductivity by the slug test in the basin, the result can be compared with other slug test experiments in other basins. Frontiere site appears here to be less permeable than Emombo's site. Despite the relatively small volume of soil that is affected by the tests, the slug tests generally reflect at least approximately the larger-scale hydraulic conductivity of aquifers [17]. This is supported by Hinsby et al. [16] who developed a new and efficient mini slug test method for the determination of local hydraulic conductivities in unconfined sandy aquifers. They realized that the mini slug test results calculated by a modified Dax slug test analysing method were in good accordance with the results from two natural gradient tracer experiments performed at the test site. Also, Butler et al. [40] proposed a new procedure for the analysis of slug tests performed in partially penetrating wells in formations of high hydraulic conductivity. They successfully used field examples of tests exhibiting oscillatory and no oscillatory behaviour to illustrate the procedure and to compare results with estimates obtained using alternative approaches. Later on, McDonald et al. [10] developed several bailer tests on large diameter wells lasting about 1h in rural water project in Nigeria to test the aquifer productivity. They found that transmissivity obtained ( $0.1-10 \text{ m}^2/\text{d}$ ) was similar to those estimated by 5 h constant rate pumping test ( $r^2 = 0.9$ ) [10]. The success of these experiments motivated the groundwater managers of the country to expand the use of such method to other rural projects. However, Cheong et al. [14] hydraulic conductivity study in an alluvial river bank of South Korea showed that the geometric mean of hydraulic conductivity (K) obtained by the slug test ( $3.08 \times 10^{-6}$  m/s) was one or two order in magnitude lower than that from pumping test ( $2.97 \times 10^{-4}$  m/s). They suggested that the lower K estimates from the slug test might be caused by disturbances in sediments around the test boreholes [14].

No matter the consistency of the Porchet test results with Kalla [7] results in the Ntem creek basin with the same method ( $2.26 \times 10^{-5}$  –  $8.17 \times 10^{-7}$  m/s); analysis of the present data brings out important information: (i) There is a substantial decreasing of hydraulic conductivity from the surface/shallow unsaturated zone to the deep saturated zone. This may be due to the variation of soil lithology with depth, although additional analysis has to be performed to explain this situation; (ii) Hydraulic conductivity data failed to correlate with the altitude ( $r = -0.20$ ); that is, the recharge areas discovered to fall within the highest elevation points do not exhibit the highest hydraulic conductivity values. Hachicha et al. [41] while studying the variability of saturated permeability on alluvial soils by three methods (Muntz, Porchet and Reynolds), realised that permeability values estimated by the Porchet and Reynolds methods were affected by the uniformity of texture and moisture and that the porchet's method presented the best correlation with respect to the soil clay content [41].

K estimates based on various empirical formula ranges from  $1.56 \times 10^{-3}$  to  $9.58 \times 10^{-5}$  m/s. The obtained values are one order in magnitude greater than the values ( $10^{-4}$  to  $10^{-6}$  m/s) obtained by Djeuda et al. [42] in the Anga'a basin by the Hazen (1892) method [42]. These estimates are consistent with the value ( $4.4 \times 10^{-4}$  m/s) obtained by Bon (2008) in the Olezoa brook basin. However, these estimates based on grain size are two to three orders of magnitude higher than the estimates from both Slug and Porchet tests. The variability in the determination of K makes it difficult to evaluate the best estimates that could represent reasonable field conditions. However, Slug and infiltration tests results appear to be more relevant than the granulometric method. *It appears that hydraulic conductivity generally decreases south-north. The river Anga'a then flows from the less permeable zone to the more permeable zone.*

The estimation of recharge by the inverse modelling was in good agreement with the hybrid method and allowed a good distribution of the recharge values within the entire river watershed. The Sensitivity tab shows a plot that is effectively the composite derivative of the calculated results at all observation points with respect to the specified parameter. As such, the plot gives more detail of an overview of parameter sensitivity. This model has four adjustable parameters, i.e.  $K_x$ ,  $K_y$ ,  $S_s$  and  $S_y$ . The plot indicates that this model is more sensitive to  $K_x$  than  $S_y$ , given the data available for calibration (Fig. 9).

## 5. CONCLUSIONS

Changes in climatological patterns within the watershed were expected to influence hydrological cycles locally. The vertical hydraulic conductivity estimate values ranged from  $9.58 \times 10^{-5}$  to  $3.55 \times 10^{-3}$  m/s after the granulometric analyses and from  $1.91 \times 10^{-7}$  to  $1.16 \times 10^{-6}$  m/s according to the infiltration test. These values appear to be falling in the domain of high to moderate permeable medium. Results showed that within the top soil, the different granulometric formulas are giving almost the same estimate of the vertical hydraulic conductivity ( $K_v$ ) value. However, these values are not adequate with the textural feature of the formation. Within the same unsaturated zone, the infiltration method indicated an average hydraulic conductivity value of  $5.90 \times 10^{-7}$  m/s, which is four level of magnitude smaller than the granulometric values, but seems to be in good agreement with the soil texture. The infiltration method then appeared to be the better technique in the estimation of the vertical hydraulic conductivity within the unsaturated zone of the investigated porous formation. Within the saturated zone, the average horizontal hydraulic conductivity ( $K_h$ ) value estimated by the slug test method is  $2.73 \times 10^{-5}$  m/s, hence indicating the anisotropic characteristic of the aquifer. Slug test came out to be a good technique for estimating saturated zone aquifer hydraulic properties because it is easy to conduct in the field and

often require only simple analysis and mathematics to interpret. Result of the estimation of the aquifer recharge by the inverse modelling method was in a good agreement with the hybrid method and allowed improving the distribution of the recharge values within the entire river watershed.

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## **COMPETING INTERESTS**

Authors have declared that no competing interests exist.

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