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Dimensional Analysis of Transmissivity Equations and Comparison of Dependent Variables Using Birnin Gwari Aquifer Characteristics in Northern Nigeria

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

This study established relationship among three transmissivity equations using dimensional analysis, comparing three dependent variables inherent in the transmissivity equations, and use correlation analysis to examine the nature of interrelationship between drawdown and specific capacity in the Birnin-Gwari local government area of Kaduna State, Nigeria between October 2018 and October 2019. Relationship between three transmissivity equations, namely, Jacob, Logan and Babuskin was determined using dimensional analysis. The equations and the outcome were applied to the hydraulic data obtained from 26 producing boreholes in the study area. Comparison of the dependent variables, namely discharge, drawdown and hydraulic conductivity, was carried out to observe the relationship among them. The Correlation analysis was used to examine the nature of interrelationship between drawdown and specific capacity, while the plots of depth-to-water table and depth-to-basement were made to provide pictorial comparison between positions of water table and the underlying Basement. The results showed that the values computed from the Jacob method are the lowest among the three, while Logan method gave higher values, although they all trend in similar manner. The study revealed an inverse trend in the

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drawdown versus discharge and hydraulic conductivity. Correlation analysis between drawdown and specific capacity gave a regression coefficient of -0.593 and correlation coefficient of 0.352, indicating a weak relationship between them. The graphical relation of water level versus basement rock surfaces portend a near-parallel trend possibly determined by the underlying geology. Transmissivity values computed from the Babuskin method gave almost average values among the three methods. Both the regression and correlation coefficients gave low to average values between drawdown and specific capacity. The depth-to-basement versus depth-to-water plots showed that water table variations are probably controlled by the type and trend of basement topography.

Keywords: Dimensional analysis; buckingham-pi; transmissivity; drawdown; hydraulic conductivity.

1. INTRODUCTION

1.1 Location, Geology and Hydrogeology

Birnin Gwari local government area (LGA) is one of the largest LGAs in Kaduna State, northern Nigeria, and occupies the north-western part of the State. It is located between latitudes 10° 22.17'N and 11° 19.57' N and longitudes 6° 04.09'E and 7° 10.91' E. Geologically, the area is underlain by the Birnin Gwari Schist Formation which is well-documented in literature, such as [1,2] among others. The formation is composed of semipelitic schists, pelitic schists, garnet and staurolite schists, pebbly and cobbly schists with subordinate gneisses. There are also greywackes, pebbly mudstones, rhyolites and dacites. The Birnin Gwari Schist Formation is bounded on either side by the Zungeru Mylonite, interpreted as reactivation zones of earlier fault zones. The formation outcrops along a major synclinal structure of which the core is occupied by the Durumi Pebbly Schist Member, and the flanks by the meta-arkoses of the Zungeru Granulite Member [3,4]. Fig. 1 shows the geological and hydrogeological map of the study area.

Hydrogeologically, extractable water in the northern Nigeria crystalline basement is found in the variably weathered zone or regolith, fractures, weathered joints and dykes. The depth and regolith weathering intensity is not necessarily a measure of its usefulness as an aquifer, because instances abound of deeply weathered areas where the regolith is relatively

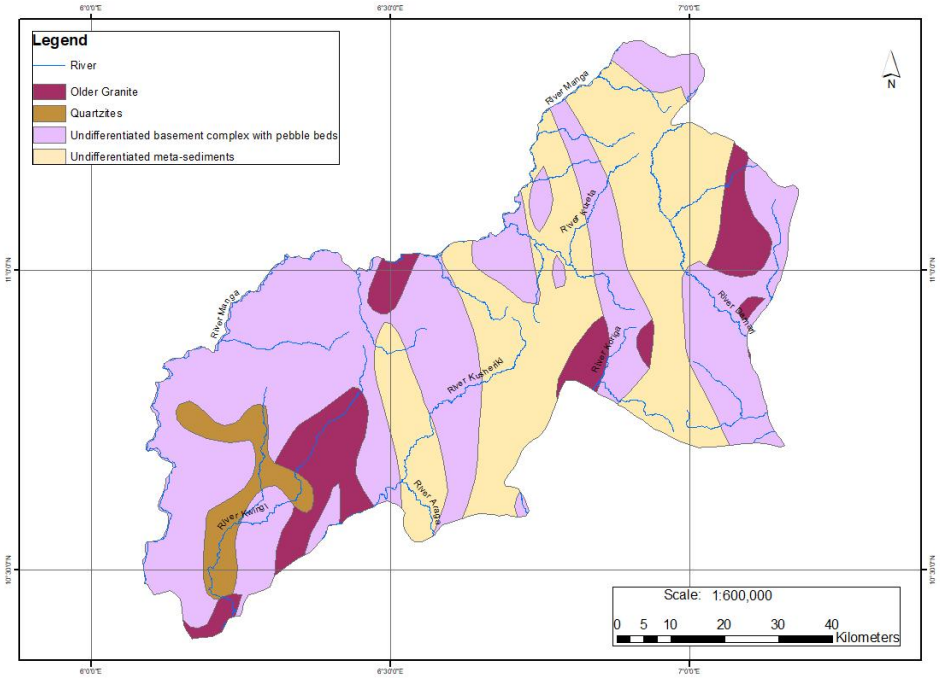

Fig. 1. Geological and hydrogeological map of Birnin Gwari local government area

impermeable. In featureless terrain with little outcrop, the aquiferous units can be better delineated by geophysical techniques. The hydrogeological properties depend on the metasediments texture, hence the schists and phyllites would be poor aquifers while the quartzites and pegmatites, where fractured, would yield significant quantities of water to boreholes. Deeply weathered schists and clay-rich metasediments in the Birnin Gwari area yield little water, whereas adjacent quartzites, scarcely weathered but strongly jointed, may be prolific aquifers [5-6].

1.2 Transmissivity and Dimensional Analysis

Transmissivity (or Transmissibility) is defined as the rate of flow of water through a vertical strip of the water-bearing material (or aquifer) of unit width and full depth under a unit hydraulic gradient and a temperature of 20°C [7]. Transmissivity is also described as the flow per unit of aquifer at right angles to the direction of flow under unit hydraulic gradient. It is used to represent the water transmitting capability of the entire thickness of the confined and semi-confined aquifers, and hence indicates how much water will move through the water-bearing formation [8]. The concept of transmissivity is valid particularly in two-dimensional, or aquifer-type flow, and is not normally used in three-dimensional flow through porous media [9].

Dimensional Analysis represents the basis upon which theoretical concepts and experiments are designed. It guides the organization of empirical data, and forms the basis for the design and operation of physical scale models which are used to predict corresponding full-scale prototype behavior. The basis of dimensional analysis is to condense the number of separate variables involved in a particular type of physical system into a smaller number of non-dimensional groups of the variables.

The main functions of dimensional analysis have been summarized [10-11] as follows:

- Determination of the number and form of dimensionless quantities which represent the similarity criteria.
- Reduction of the numbered independent variables in an experiment, simplification of the solution and generalization of its results.
- Conversion of the basic set of units of the measurement,
- Conversion of physical quantities into another basic set of units of measurement,
- Determination of functional relations in cases where the solver does not know more detailed information of the physical principle of the investigated phenomenon and no complete mathematical description of the phenomenon is known.

In the application of dimensional analysis, the highest efficiency is reached in its combination with general physical ideas obtained by a solver directly from experiments. The depth of previous knowledge of the physical principles of the investigated phenomenon can influence and extend considerably the possibilities of the dimensional analysis [11].

The basic dimensions in engineering can be used to express all the physical parameters or variables. These basic dimensions, which are mass [M], length [L] and time [T], are sufficient for dimensional analysis [12]. A physically sound equation describing a physical phenomenon must be dimensionally homogeneous in that all terms in the equation must have the same dimensions. Three major methods used in analysis are the Indicial method, Buckingham-π method, and the Matrix method. One basic theorem in dimensional analysis is the Buckingham-Pi theorem and it states that, for a problem involving N independent physical variables and M basic dimensions, $N - M$ independent dimensionless group of variables can be formed. Therefore, in designing empirical correlations and scale models, only the $N - M$ dimensionless groups need to be considered rather than the original N variables in order to describe completely the flow phenomena. In addition, a relationship among the dimensionless groups relevant to a problem is automatically dimensionally homogeneous, and as such satisfies a requirement for a physically sound description [13-14].

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 [15].

1.3 Objective

The main objective of this study, therefore, is to formulate a relationship between commonly used transmissivity equations by using dimensional

analysis, and the equations with the resulting outcome of the analysis applied to the borehole data from the basement aquifers of the Birnin Gwari LGA of Kaduna State, Nigeria. Some inter-relationships were also considered among other aquifer parameters of the study area.

2. MATERIALS AND METHODS

The study considered the three commonly used transmissivity equations, namely, the semi-equilibrium Jacob analytical method, the Logan method and the Babuskin approximate method and attempted establishing a relationship among them using dimensional analysis through the Buckingham-Pi theorem. The three transmissivity equations as well as the resulting outcome of the analysis were applied to the hydraulic data obtained from 26 producing boreholes drilled across the basement aquifers of the Birnin Gwari local government area of Kaduna State, Nigeria. Furthermore, a comparison of the dependent variables inherent in all the transmissivity equations, namely discharge, drawdown and hydraulic conductivity, was carried out to observe any trending relationship among them. The Pearson Product Moment Correlation analysis was used to examine the nature of interrelationship between drawdown and specific capacity, while the plots of depth-to-water table and depth-to-basement were made with a view to comparing pictorially the relative water table positions with respect to the underlying Basement rocks.

3. RESULTS AND DISCUSSION

3.1 Dimensional Analysis of Transmissivity Equations

Three of the major methods of determining Transmissivity are the semi-equilibrium Jacob analysis [16–18], the Logan method [19,20] and Babuskin approximate method [21,22]. The Jacob method of analysis is represented by the following equation:

$$T = \frac{2.3Q}{4\pi D} \tag{1}$$

where T is the transmissivity in $m^2.day^{-1}$, Q is the discharge in $m^3.day^{-1}$, and D is the drawdown over one log cycle in meters. The Logan method of computing transmissivity, T ($m^2.day^{-1}$) is expressed [20] by the equation:

$$T = \frac{1.28Q}{D} \tag{2}$$

Where Q is the discharge in $m^3.day^{-1}$, and D is the maximum drawdown. Babuskin evolved a relationship for determining the hydraulic conductivity, K, given as:

$$K = \frac{0.366Q}{LD}\log\frac{1.32L}{r_w}$$

where K is measured in $m.day^{-1}$, Q is borehole discharge in $m^3.day^{-1}$, L is the length of screen (m), D is the drawdown (m) and r_w is the radius of the borehole (m). Using the calculated value of K from the above equation (2), transmissivity can then be calculated from the relationship $T = Kh$, where h is the thickness of the aquifer. The resulting equation for determining Transmissivity can then be given as:

$$T = \left[\frac{0.366Q}{LD}\log\frac{1.32L}{r_w}\right]h \tag{3}$$

From equations (1), (2) and (3), the variables describe the flow and geometric properties of an aquifer. Transmissivity is the independent variable while the corresponding dependent variables are Q, D, K and h. Each quantity can be reduced to its fundamental dimensions as follows:

$$T = [L^2T^{-1}], Q = [L^3T^{-1}], D = [L] and h = [L].$$

The transmissivity equation, using λ as a dimensionless coefficient, may be assumed to be:

$$T = \lambda h\left[Q^a \cdot D^b \cdot K^c\right] \tag{4}$$

Where λ is a constant and a, b, and c are unknown powers. Expressing each quantity in Equation (4) in terms of its dimensions gives:

$$L^2T^{-1} = \lambda h\left[(L^3T^{-1})^a \cdot L^b \cdot (LT^{-1})^c\right] \tag{5}$$

These dimensional relationships may be expressed in matrix form as follows:

$$\begin{matrix} & T & Q & D & K \\ L & 2 & 3 & 1 & 1 \\ T & -1 & -1 & 0 & -1 \end{matrix} \quad (6)$$

The principle of homogeneity makes it possible to determine the exponents *a, b* and *c* by equating the sum of indices as follows:

$$\begin{aligned} &For\ L, \quad 2 = 3a + b + c \\ &\quad T, -1 = -a - c \\ &\Rightarrow \quad a = 1 - c \\ &and \quad b = 2c - 1 \end{aligned}$$

Substituting for *a* and *b* in equation (4), the result becomes

$$T = \lambda h\left[Q^{1-c} \cdot D^{2c-1} \cdot K^{c}\right]$$
$$\Rightarrow \quad T = \lambda h \frac{Q}{D}\left[\frac{K D^{2}}{Q}\right]^{c} \quad (7)$$

Applying Buckingham-π theorem to equation (7),

$$\pi_1 = \frac{DT}{Qh} \quad (8)$$

$$\pi_2 = \frac{KD^2}{Q} \quad (9)$$

With *D, Q and T* as governing variables,

$$\pi_1 = D^a Q^b T = L^0 T^0$$
$$\Rightarrow \quad \pi_1 = L^a \left[L^3 T^{-1}\right]^b \cdot \left[L^2 T^{-1}\right] = L^0 T^0$$

For dimensional homogeneity, the indices are equated as follows:

$$\begin{aligned} &For\ L, \quad a + 3b + 2 = 0 \\ &\quad T, \ -b - 1 = 0 \\ &\Rightarrow \quad b = -1 \\ &and \quad a = 1 \\ &\therefore \quad \pi_1 = D Q^{-1} T h^{-1} \\ &or \quad \pi_1 = \frac{DT}{Qh} \end{aligned} \quad (10)$$

Similarly, with *K, D* and *Q* as governing Variables,

$$\pi_2 = \frac{KD^2}{Q}$$
$$\pi_2 = K D^a Q^b = L^0 T^0$$
$$\Rightarrow \quad \pi_2 = \left[L^2 T^{-1}\right] L^a \left[L^3 T^{-1}\right]^b = L^0 T^0$$

Equating indices,

$$\begin{aligned} &For\ L, \quad 2 + a + 3b = 0 \\ &\quad T, \ -1 - b = 0 \\ &\Rightarrow \quad b = -1 \\ &and \quad a = 1 \\ &\therefore \quad \pi_2 = KDQ^{-1} \\ &or \quad \pi_2 = \frac{KD}{Q} \end{aligned} \quad (11)$$

$$\begin{aligned} &But \quad \pi_1 \times \pi_2 = 1 \\ &or \quad \pi_1 = 1 \big/ \pi_2 \\ &\therefore \quad \frac{DT}{Qh} = \frac{KD}{Q} \\ &\Rightarrow \quad T = Kh \end{aligned} \quad (12)$$

The relationship obtained as equation (12) agreed with [7,13,23,24] who variously defined transmissivity, *T* as the product of the hydraulic conductivity, *K* and the thickness, *h* of the aquifer. Since *K* was based on the Babuskin formula for this study, equation (3) will then be applicable in the place of equation (12) for the determination of transmissivity.

Each of the equations (1), (2) and (3) was used to compute the transmissivity values for each of the 26 wells, and the results were plotted into the graph presented as Fig. 2. From the figure, a linear and parallel relationship evolved between the values obtained from the three methods. However, the values computed from the semi-equilibrium Jacob analytical method are observed to be generally the lowest among the three, followed by those obtained from the Babuskin approximate method, while the Logan method gave values that are somewhat higher, although they all depict a similar trend from one location to the other. The lowest values of transmissivity, *T* occurred at Sarkin Pawa, while the highest values were found at Ungwan-Musa-

Kurara. Low *T* values are typically characteristic of the underlying crystalline aquifers in the area except where they are highly fractured [22].

3.2 Comparison of Dependent Variables

Fig. 3 shows a comparison of three variables, that is, hydraulic conductivity, discharge, and drawdown which are among the dependent variables inherent in the transmissivity equations. These aquifer properties are generally considered to be of significance for groundwater development. The figure shows a direct linear relationship between discharge and hydraulic conductivity, and a non-parallel relationship of these two parameters with drawdown. This is because the values of drawdown revealed a different trend from those of discharge and hydraulic conductivity. In other words, it can be deduced that the there is an inverse trend between drawdown on one hand, and discharge and hydraulic conductivity on the other hand; as drawdown increases discharge and hydraulic conductivity decreases, and vice-versa.

The range and mean values of the major variables used in the transmissivity equations applied to the Birnin Gwari aquifers, as well as the range and mean values of transmissivities computed by using the three methods for the 26 well locations across the study area are presented as Table 1. The maximum value of discharge obtained in the area is 172.8 $m^3.day^{-1}$, while that of hydraulic conductivity is 1.83 $m.day^{-1}$; both occurred at Ungwan-Musa Kurara, and their corresponding lowest values of 21.6 $m^3.day^{-1}$ and 0.033 $m.day^{-1}$ both coincided together at Sarkin-Pawa area. However, the highest value of drawdown, 28.3m occurred at Sarkin-Pawa where the values of other parameters are lowest, while the lowest value of 6.4m was found to be at Shado. This shows that maximum drawdown occurs where there is low yield.

It will be observed in Table 1 that there are differences between the values found by the Jacob, Logan and Babuskin methods. The Jacob method, which later became Jacob and Cooper method [25], was modified from the original Theis solution for transient flow to a well discharging at a constant rate from an homogeneous and isotropic non-leaky confined aquifer. The Jacob solution is, therefore, an approximate derivative, and the Logan and Babushkin methods are further modifications under specific conditions for the estimation of transmissivity. While discharge and drawdown are the common variables in the three methods, the resultant values of coefficients of these variables in the Jacob and Logan methods are different, and Babushkin method introduced other variables, namely length of screen and borehole radius into the determination of transmissivity. Hence there are differences in the transmissivity values obtained, although the values peaked at the same locations (Fig. 2) and dropped at the same locations. Consequently, it may be inferred that any of the methods can be used since the information pattern remains the same.

3.3 Pearson Product Moment Correlation Analysis of Drawdown and Specific Capacity

While drawdown is the difference between the static water level and the pumping water level measured at the same instant, specific capacity is defined as the yield of a well per unit of drawdown, provided that both quantities are also measured at the same time. Drawdown affects the yield of a well, and specific capacity gives a better indication of aquifer performance than yield. In Fig. 4, the Pearson Product Moment Correlation analysis was used to examine the degree and nature of interrelationship between drawdown and specific capacity at the 26 borehole locations, and it was found that the regression line of drawdown on specific capacity gave a coefficient of -0.593, while the correlation coefficient is 0.352. Both the regression and correlation coefficients gave average to low values, indicating a weak relationship between the two parameters, while the negative regression value shows that as specific capacity increases, drawdown decreases gradually, although their true relationship may require more than such a simplified linear model. The value of drawdown is lowest at Shado while the specific capacity is lowest at Sarkin Pawa. Low drawdown is indicative of good storage capacity, while low specific capacity reflects poor aquiferous condition. While Shado is underlain by the fractured quartzites and pegmatites, Sarkin Pawa lies on the schists and phyllites which are poorly aquiferous even where the aquifer is fractured; storage capacity is low and yield is sustained by the surrounding regolith through porous flow.

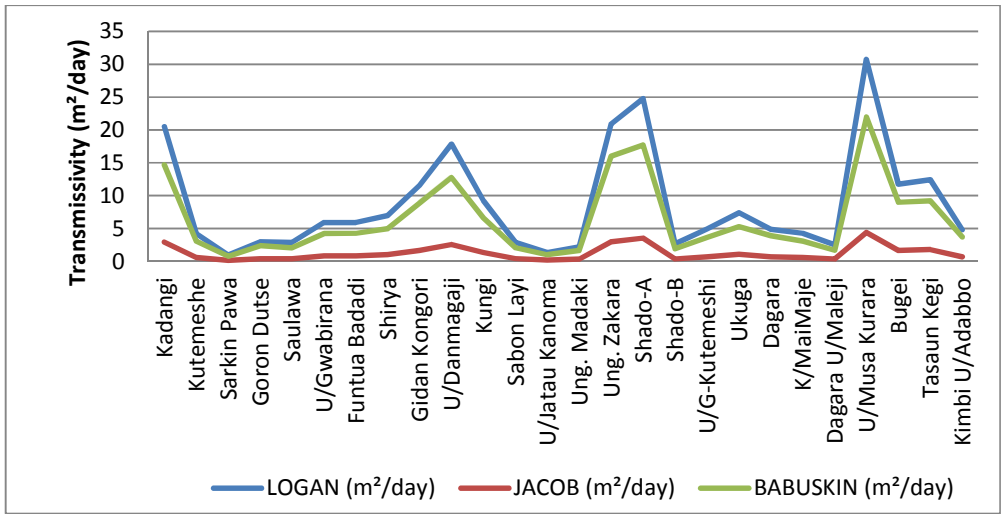

Fig. 2. Graphical comparison of transmissivity values from three methods

3.4 Graphical Relationship between Depth to Water Table and Depth to Basement

The relationship between the depth to water table and depth to basement from the ground surface was compared in order to observe pictorially their lateral variation and relative positions along these depths as shown in Fig. 5. From the figure, both surfaces showed near-parallel variation from one location to the other. Water table exists generally within the weathered basement complex rocks of the area at varying depths, and the variations are determined by the trend of the underlying basement topography. The thickness of the pay-zone which is the effective thickness of the regolith that may influence groundwater storage also vary laterally. The shallowest depth to the underlying Basement rock of 4 m occurred at Sabon-Layi, while the basement depth is greatest at Ungwan Gwabirana to as much as 44 m. On the other hand, the water table existed at a shallow depth of 3.8 m at Dagara, whereas prospectors for groundwater may have to drill as much as 21.3 m to encounter the water table at Ungwan Gwabirana.

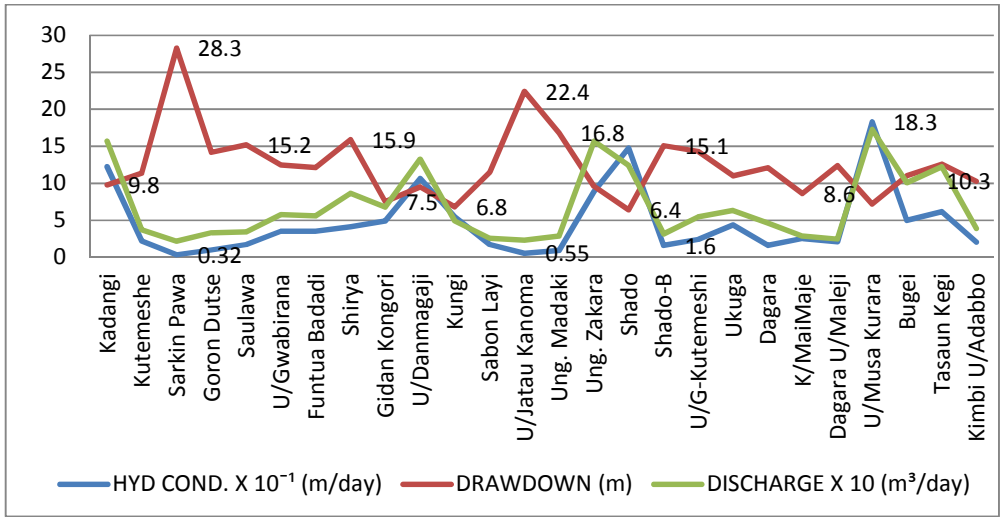

Fig. 3. Comparison of some dependent variables in transmissivity equations

Table 1. Range and mean values of variables from birnin gwari aquifers

	Discharge	Drawdown	H/Cond.	Aq.Thick	Sp. Cap.	Transmissivity ($m^2.day^{-1}$)		
Unit	$m^3.day^{-1}$	*m*	$m.day^{-1}$	*m*	*l/min/m*	Jacob	Logan	Babuskin
Max.	172.8	28.3	1.83	24	16.76	4.39	30.72	21.96
Min.	21.6	6.4	0.032	8	0.53	0.14	0.97	0.78
Mean	68.28	12.48	0.47	15	6.85	1.81	12.66	9.18

(H/Cond = Hydraulic Conductivity; Aq.Thick = Aquifer Thickness; Sp. Cap. = Specific Capacity)

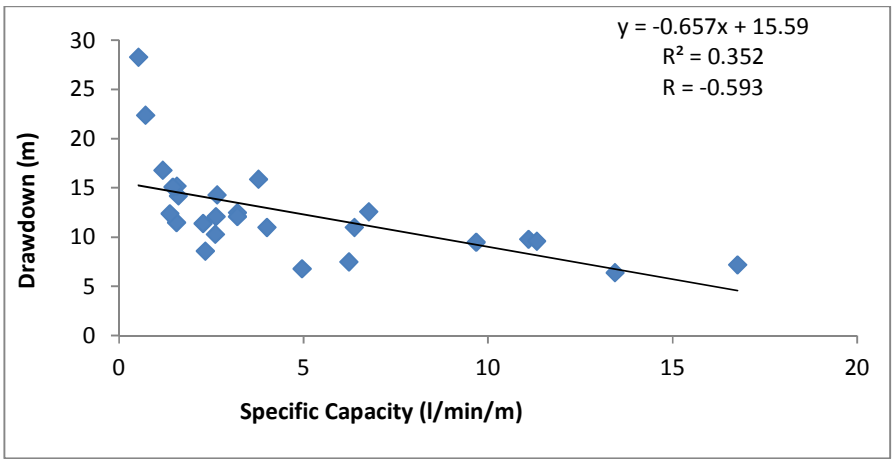

Fig. 4. Regression of drawdown on specific capacity

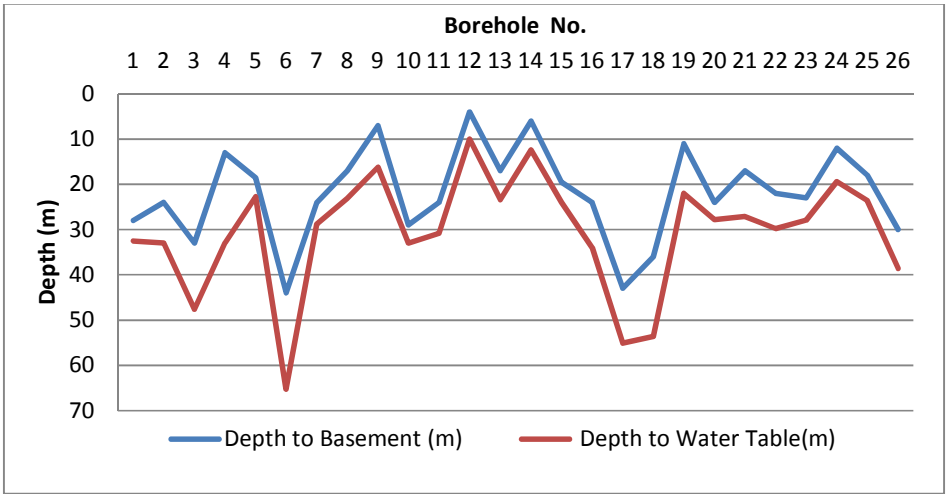

Fig. 5. Relation between depth to water table and depth to basement

4. CONCLUSION

The dimensional analysis of three commonly used transmissivity equations was carried out using the Buckingham-Pi method with a view to establishing a relationship among them. The three equations and the solution obtained were applied to the borehole data obtained from 26 boreholes drilled across the LGA.

The results showed similar trending values, but the values computed from the semi-equilibrium Jacob analytical method are the lowest among the three, followed by those obtained from the Babuskin approximate method, while the values from the Logan method are found to be fairly higher. This may be attributed to the fact that while discharge and drawdown are the common variables in the three methods, the values of

coefficients of these variables in the Jacob and Logan methods are different, and the Babushkin method introduced other variables, namely length of screen and borehole radius which affect the value of transmissivity. It may be inferred that any of the methods can be used since the pattern of outcome remains the same. The values of three dependent variables, namely discharge, drawdown and hydraulic conductivity were compared and it was found that there is an inverse trend between drawdown on one hand, and discharge and hydraulic conductivity on the other hand, such that as drawdown increases discharge and hydraulic conductivity decreases, and vice-versa. The relation between drawdown and specific capacity was examined by applying the Pearson Product Moment Correlation analysis, and it was found that both the regression and correlation coefficients gave low to average values, indicating a weak relationship between the two parameters, and that as specific capacity increases, drawdown gradually decreases. The depth-to-basement rock versus depth-to-water table graphical relation showed that water table exists generally within the weathered basement complex rocks of the area at varying depths, and the variations are probably determined by the trend of the basement topography.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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