Hydrogeology

HYDROGEOLOGICAL ASSESSMENT OF CRISTALLINE ROCK MASS AQUIFER SYSTEM

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ABSTRACT

The practical application of analytical method to crystalline aquifer system in Southwestern Nigeria is rare in hydrogeological literature. The subject matter includes formulae to quantitatively appraise the hydraulic parameters influencing the water-yielding capacity of tube wells which tap a crystalline aquifer rock mass. Pumping test was carried in a total of 20 tube wells at a controlled rate and water-level response was measured, 5 from each from Ilorin, Abeokuta, Ibadan and Akure. The rise in water levels was recorded as residual drawdown, s’, and the water level measured at a residual time t’ after the pump has been turned off. This solution was applied to residual drawdown data, which involves fitting a straight line on a residual drawdown plot of s’ (residual drawdown) versus log t/t’. Hydraulic properties were estimated with discharge, drawdown and specific capacity data.

It was found necessary to account for effects of mode of geological formation and mineralogical composition in order to be satisfied with variations in measured and estimated hydraulic parameters, particularly drawdown and transmissibility. These help to ascertain the low values of discharge in the crystalline aquifer system. The values of the hydraulic parameters are consistent with what obtains in the crystalline aquifer system. The average estimated values are: discharge, $8.0 \times 10^{-4}$ m$^3$/s; specific capacity $1.31 \times 10^{-4}$ m$^2}$/s; well loss constant $3.14 \times 10^7$ s$^2$/m$^5$; transmissibility 94.8 m$^2$/day.

Further research should employ precise, quantitative data concerning requisite geologic information about crystalline rock aquifer system.

INTRODUCTION

On a global scale, the Southwestern Nigeria Basement Complex approximately lies between latitudes 7°N - 10°N and longitudes 4°E - 6°E in the Equatorial Rain Forest Region of Africa. It is a geotectonic complex, whose surface area constitutes over 75% of the Precambrian rocks of the Basement Complex (Burke and Dewey, 1972; Burke, et al. (1976; Ajibade, et al. 1987). Rahman (1988) corroborated by Oyinloye (2011) reveal 3 major geotectonic events in the evolution of the Precambrian rocks, namely;

(i) initial crust forming process during the Early Proterozoic (2000Ma) typified by the Ibadan grey gneisses derived directly from the mantle,
(ii) emplacement of granites in Early Proterozoic (2000Ma) and
(iii) the Pan African Orogeny (450Ma-750Ma).

In hydrogeology, a crystalline aquifer material is studied from the point of view of mineralogical composition, tectonic history and metamorphism. The area under study shown in figure 1 is specifically underlain by extensive mass of the Older Granite Series which grade into the surrounding country rocks of the Migmatite Gneiss Complex. Rahman (1988), and Badmus and Olatinsu (2010) further enumerate the main rock types in Southwestern Nigeria as folded gneisses, schists, quartzite, Older granite, and amphibolites/mica schist.

Tropical climate characterized by alternating wet and dry seasons is of significant influence on weathering of the Migmatite Gneiss Complex rocks. The wet season usually is between March and October with heavy
curate estimation of aquifer properties from grain-size distribution data crucial for successful groundwater development and management practices. However, this method is inadequate as its ability to define precisely, aquifer geometry and hydraulic boundaries is limited to sedimentary basins. By comparison, Ofodile, (1992) is of that the idea that more productive aquifers occur in sedimentary geologic formations than in weathered and fractured crystalline rocks. Tijani and Nton (2009) employ textural characteristics to define the hydraulic conductivity of the Ajali sandstone in the Anambra Basin.

Classical analytical method of pumping test is expensive and depends on aquifer's hydraulic boundaries and geometry, but remains the only reasonable procedure for obtaining accurate transmitting properties in the Basement aquifer. In hydrogeological literature, the petrology of the Basement Complex has a considerable influence on flow direction and potential zones of groundwater. Ofodile (2002) shows that over 50% failure rates have been recorded from the boreholes drilled so far in the Basement Complex area. However, favourable geophysical and geological evidences improved the chances of locating joints and fracture zones in order to obtain a considerable amount of water from this source. This is evident as most crystalline rocks in Nigeria are located in high relief areas where runoff is high and infiltration rate is low. These are complemented by tropical climatic condition, as the crystalline rocks weather more easily and deeply only under humid condition.

High cost of drilling tube wells hindered intensive research on hydrogeology of crystalline rocks in Nigeria. However serious research began in recently times, due to rapidity in urban development and improved economy. In this research work emphasis is placed on the quantitative evaluation of the practical yields of wells and aquifer by field and analytical methods. The hydraulic properties of the aquifer and appropriate ground-water formulae are used to construct a mathematical model which provides a means of evaluating the performance of the crystalline aquifer system. This will enable a workable data can be obtained from a considerable number of tube wells, which are widely distributed in the Southwestern Nigeria. It is expected that this simple approach to organizing, conducting,
and interpreting complex aquifer test data will turn into information that is understandable and useful to better explain the low values of yield often reported for crystalline aquifers in the literature.

**HYDROGEOLOGY**

The occurrence of groundwater in the Basement Complex of Southwestern Nigeria is a function of the extent and depth of weathering as well as fracturing of the crystalline rocks (Offodile, 2002). Normally, Basement aquifers are developed within either the regolith (relatively high storativity but low permeability) or the fractured bedrock (low storage capacity with a relatively high permeability). Barker (1988) reveals that groundwater is contained in the weathered/ fractured formations and primarily recharged through surface precipitation, and secondarily through lateral flow from rivers and tributaries. The water table in crystalline rock is partly phreatic and partly piezometric (Fig. 2). In the rock mass, the joint planes act as water barrier. The water table is inclined and follows a general topography of the ground. Inflow of water comes from infiltrated rain fall, while outflow of water takes place in springs or rivers. The hydraulic pressure of the water in a rock depends on the depth below the water surface, and works on the face at both sides of the joint with a tendency to open the joint.

Groundwater flow in the Precambrian crystalline basement rocks occurs in shallow cracks and joints opened by weathering. Water flows through the intergranular matrix but the presence of fractures enhances the permeability (Gale 1982). Yields of occasional springs as explained by Moore (1997), are small except where tectonic influences have enhanced the secondary porosity. The crystalline rocks in the study area have some primary permeability in weathered zones but the principal, secondary permeability is developed in joints and fissures which provide sustainable borehole yields and of good quality.

The depth at which fractures and joints in the crystalline rock become completely saturated with water marks the water table. Groundwater in the study area is recharged from, and eventually flows to, the surface naturally. Water flows directly between the surface and the saturated zone of an overburden aquifer, which is unconfined. The deeper parts of unconfined aquifers are usually more saturated since gravity causes water to flow downward.

Ofodile, (1979) Butler et al. (2001 )and Badmus and Olatinsu (2010) note that the characteristics of basement aquifer vary with the mode of geological formation, mineralogical composition and structure of the substrate as well as the topography in which they occur. Generally, fractured crystalline rocks yield smaller quantities of groundwater in many environments in comparison with sedimentary aquifer. This makes it an important resource which can act as a natural storage that can buffer against shortages of surface water, as in during times of drought. Groundwater is naturally replenished by surface water from rivers when this recharge reaches the water table.

**METHOD OF RESEARCH**

Pumping test was carried out as a controlled field ex-
periment in a total of 20 tube wells, 5 from each from Ilorin, Abeokuta, Ibadan and Akure. The wells were pumped at a controlled rate and water-level response was measured optionally in the pumped wells. When the pump was shut down after a pumping test, the water level in the well and the piezometers was allowed to rise. This rise in water levels was recorded as residual drawdown, $s'$, and expressed as the difference between the original water level before the start of pumping and the water level measured at a residual time $t'$ after the pump has been turned off.

The Theis (1935) solution was applied to residual drawdown data following the BSI (1992), Boonstra (1992), Kruseman and de Ridder, (1994), USBR (1995), Brassington (1998) and Hund-Der and Chih-Tse (2009) recovery test method for estimating aquifer properties from the recovery data. This involves fitting a straight line on a residual drawdown plot of
Results Presentation and Discussion
The crystalline rock mass is highly heterogeneous when examined at a scale similar to the spacing of the dominant pore size. The consequence of this is that Darcy’s law can be used successfully, but only at a scale large enough to contain a representative assemblage of pores. This is the continuum scale. At sub-continuum scales, the local pore network geometry strongly influences flow and the transport of contami-

s’ (residual drawdown) versus log t/t’ (ratio of time since pumping began to time since pumping stopped) in reverse order as discussed in Clark (1977). Selected plots from each of the testing locations are shown in Figures 3, 4, 5 and 6. This will enable the estimation of basic hydraulic properties of the aquifer under study. Discharge (Q) of each well was estimated and derivative analysis was used based on Chenini et al. (2008) to further quantitatively appraise the aquifer.
nants. This is particularly relevant in fractured rocks where the dimension of the fracture spacing can impart a continuum scale that exceeds the size of many practical problems. Results of the aquifer parameters are summarised in Table 1. The studied rock mass aquifer system yields (Q) up to $1.3 \times 10^{-3}$ m$^3$/s with residual drawdown ($s'$) ranging between 2.3 m and 55 m. Average static water level (SWL) is 11.90 m within a range of 0.6 m – 51 m, while depth ranges between 19 m and 82 m. Mean specific capacity ($c_s$) and well loss constant ($c$) are $1.31 \times 10^{-4}$ m$^2$/s and $3.41 \times 10^7$ s$^2$/m$^5$ respectively, with maximum transmissibility (T) of 39.57 m$^2$/day. Among the aquifer properties, only specific capacity ($c_s$) is the least variable parameter, having coefficient of variation (cv) of 5%. This is in agreement with findings of Knopman, and Holliday (1993). In general, all other parameters have coefficient of variation above 10%. This implies that the variation caused by the aquifer system on SW, SWL, BHD, Q, C and T is high enough to be significant (Rag, 1972).

A relationship is established between drawdown and discharge in the aquifer system (Fig. 3). The regression plot of drawdown ($s_w$) against discharge ($Q$) is shown in Figure 7. The equation is $s_w = 19.4Q - 0.35$ with $r = 0.42$ and $r^2 = 0.18$. Among the aquifer parameters, only specific capacity ($c_s$) is the least variable parameter, having coefficient of variation (cv) of 5%. This is in agreement with findings of Knopman, and Holliday (1993). In general, all other parameters have coefficient of variation above 10%. This implies that the variation caused by the aquifer system on SW, SWL, BHD, Q, C and T is high enough to be significant (Rag, 1972).
sion analysis shows that very low positive correlation \((r = 0.42)\) exists between the drawdown and discharge in the aquifer system, with coefficient of determination equals 0.18. The implication is that drawdown increases with increasing discharge, and estimation of discharge from drawdown data is not reliable. However, 18\% of the variation in drawdown was associated with discharge in the studied crystalline rock aquifer system.

Specific capacity \((c_s)\), well loss constant \((c)\) and transmissibility \((T)\) are the major derived hydraulic properties of aquifer, upon which the foundation of quantitative groundwater studies can be based. Specific capacity is a quantity of water which a well can produce per unit of drawdown. Although, it is useful for comparing the efficiency of the same well through time but due to non-linear well losses, the specific capacity will decrease with higher pumping rates. This complication makes the absolute value of specific capacity of little use. Well loss can be explained in two ways; linear head loss and non-linear head loss. Linear well loss is caused by the aquifer being damaged during the drilling and completion of the well. It comprises, head losses resulting from the aquifer material compacting during drilling; head loss resulting from the aquifer becoming plugged with drilling mud, which reduces the permeability near the bore hole; head loss in the gravel pack; and head loss in the screen. The general equation describing the drawdown \((s_w)\) in a pumped well as function of aquifer well loss \((c)\) and discharge \((Q)\) thus reads:

\[
C = \frac{s_w}{Q^n} \quad (1)
\]

Experience has shown that in fractured rock aquifers \(n\) value may even exceed 3.5, but the \(n\) value equals 2 is widely accepted. Kruseman and de Riddler, (1994) classified well deterioration on the basis of well loss coefficient. Well loss coefficient \((C)\) ranging between \(1.9 \times 10^4 \text{ s}^2 / \text{ m}^2\) and \(3.8 \times 10^5 \text{ s}^2 / \text{ m}^2\) indicates mild well deterioration, while \(C\) value above \(3800 \text{ s}^2 / \text{ m}^2\) is indicative of severe well deterioration. The estimated \(C\) values of the studied wells range from \(2.33 \times 10^8 \text{ s}^2 / \text{ m}^4\) to \(7.56 \times 10^6 \text{ s}^2 / \text{ m}^4\). This implies that all the studied wells are severely deteriorated. Other important engineering aspect of rock mass with respect to groundwater is the transmissibility \((T)\). In practice, however, Equation 2 (expressed in \(\text{ m}^2 / \text{ s}\)) as given by Discroll (1986) and Razack and Huntley (1991), have been found to be adequate in most cases, as against the equation of Cooper and Jacob (1946). This is modified to Equation 3 to enable determination in \(\text{ m}^2 / \text{ day}\).

\[
T = \frac{Q}{s_w} \cdot 1.2 \quad (2)
\]

\[
T = \frac{Q}{s_w} \cdot 4.11 \times 10^6 \quad (3)
\]

Gheorghe (1978) defines the transmissibility potential of aquifer as summarised in table 2. The studied aquifer rock mass have \(T\) values which range between \(39.57 \text{ m}^2 / \text{ day}\) and \(1.42 \text{ m}^2 / \text{ day}\). It follows that the studied aquifer is of low transmissivity potential. The variations in transmissibility and drawdown are extremely high, while the values of hydraulic parameters are consistent with what is known about the crystalline aquifer. Effects of fractures and mineralogical composition are suspected to be responsible for these (Stefan and Vitaly, 2005). In the analysis of crystalline aquifer test data borehole depth and aquifer yield vary relatively.

<table>
<thead>
<tr>
<th>TRANSMISSIBILITY ((T)) RANGE ((\text{ m}^2 / \text{ day}))</th>
<th>CLASS</th>
</tr>
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<tr>
<td>(&gt; 500)</td>
<td>High Potential</td>
</tr>
<tr>
<td>(50 – 500)</td>
<td>Moderate Potential</td>
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<tr>
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<td>(0.5 – 5)</td>
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<tr>
<td>(&lt; 0.5)</td>
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**Table 2:** Transmissivity potential of aquifer system (After Gheorghe, 1978)

**CONCLUSIONS AND RECOMMENDATIONS**

Evaluation of aquifer properties is often possible with analytical methods by devising approximate methods of analysis based on idealized models of an aquifer system. Diverse results and variations arise in the attempt to force the application of ideal conditions formulae to crystalline aquifer situations. Variations of estimated aquifer parameters indicate that the crystalline nature of the aquifer actually does coincide rather closely with what may be predicted theoretically with model aquifers and mathematical models.
### APPENDIX 1

<table>
<thead>
<tr>
<th>Location</th>
<th>Drawdown (Sw) m</th>
<th>Static Water Level (SWL) m</th>
<th>Borehole Depth (BHd) m</th>
<th>Discharge (Q) m³/s</th>
<th>Specific Capacity Cs = Q/sw m²/s</th>
<th>Well loss Constant C = sw/Q² s²/m</th>
<th>Transmissibility T = Q/sw.2.1 m²/s</th>
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It is apparent that quantitative answers to explain the behaviour of the crystalline aquifer system depend primarily upon the geologic and hydrologic controls. As the general technique of groundwater resource evaluation is inadequate, a need for more precise, quantitative data concerning requisite geologic information about crystalline aquifer is strongly recommended. Formulas and methods should not be used to evaluate a crystalline rock aquifer without due regard to mode of geological formation as well as mineralogical composition.

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