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ESTIMATION OF AQUIFER PRODUCTIVITY AND GROUNDWATER RECHARGE FROM SINGLE - WELL PUMPING TEST

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ABSTRACT

Due to the abrupt variations in lithology and structures associated with crystalline basement terrains of southwestern (SW) Nigeria, reliable evaluations of aquifer properties are essential for the management and protection of groundwater resource. For this purpose, single-well pumping and recovery tests were carried out in wells within the various bedrock terrains of Ibarapa region of SW Nigeria to evaluate the discharge, drawdowns, storage capacity, transmissivity, recovery rate and other well inventory with the aim of evaluating sustainable groundwater yield within the diverse geological terrains of the region of study. From the results, the average (av.) groundwater discharge (in m^3/day) for wells in areas underlain by amphibolite was 72.05; 53.45 in gneisses; 68.27 in migmatite and 64.33 in granitic terrains. In the respective order of geological settings, the total drawdowns in wells were 10.70 m, 21.99 m 17.69 m and 15.58 m and transmissivities (in m^2/day) were 6.85, 2.57, 0.76, 1.72, while specific capacity values (in m^3/d/m) were correspondingly; 7.67, 3.10, 4.00 and 5.54. The recovery tests showed that wells in granitic terrains were characterized by better water recharge than in other terrains. However, groundwater yield in amphibolite and to a lesser extent in gneisses were quite sustainable and the rates of groundwater recovery though moderate sustained continuous discharge for hours of continuous pumping. It is therefore mandatory to develop a reticulation system in this region so as to cater for water supply in areas underlain by granite and migmatite at the central and north-eastern part of the study area.

KEYWORDS: basement terrains, sustainable, transmissivity, water-bearing, yield

INTRODUCTION

Approximately half of the world citizens rely on groundwater for domestic, industrial and agricultural utilisation (Siebert, 2010). This is more so in sub-Sahara Africa and parts of Asia, where there is continual increase in population and the attending growths in agricultural and industrial activities that have led to greater need for expansion of social amenities including water supply and electricity. In this respect, areas underlain by crystalline rocks with low potential for groundwater occurrence are now being investigated in detail for groundwater development, (Heath, 1983; Danskin, 1998; Akanbi, 2018). Most crystalline rocks erstwhile called 'hard rocks' are characterized by negligible primary porosity and permeability, and ordinarily have little or no groundwater potential. However, considerable groundwater zones can develop under intense weathering and fracturing and significant regolith thickness can develop over the fresh bedrocks. It is known that saprolite layer of 5 m in thickness may form potential aquifers as long as there is a recurrent groundwater recharge (Singhal and Gupta, 1999). In Nigeria, domestic groundwater supply has become substitute to public town water supply as a result of the gross inefficiency and the break-down of the conventional piped water supply schemes and reliance on groundwater for various usages has increased tremendously in the last three decades (Tijani, 2016, Akanbi, 2017). It has also been projected that by year 2030, there will be a deficit of over 17 billion litre/day of water supply based on water supply-demand estimations (Ojo et al. 2004)

However, most groundwater development

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investigations in hard rock terrains focussed on the description of the lithology of the weathered-fractured zones using geophysical methods, and chemical evolution of the enclosed water within the crystalline water-bearing zones. (Jones, 1985; Acworth, 1987; Chilton and Foster 1995, Singhal and Gupta 1999 and Holland, 2011; Akanbi, 2016; 2018; Akanbi and Olukowade, 2018). Studies in respect of hydraulic characterisation of crystalline aquifers are less documented or published in developing world including Nigeria compared to developed nations of the world such as in North America and in Europe. But, studies of geo-hydrological attributes of sub-surface environments are crucial for guaranteeing sustainable yield of groundwater resource (Oladapo and Akintorinwa, 2007; Jayeoba and Oladunjoye, 2013; Akanbi, 2016; Tijani, 2016). The lack of the understanding of the occurrence, movement and recharge processes of groundwater in basement terrain has frequently contributed to the failure of many boreholes in hard rock areas, even in other nations as well (UNESCO, 1984; Chilton and Foster, 1995; Holland, 2011). Therefore, for guaranteeing sustainable groundwater yield, hydraulic characterisation of the water bearing zones and the understanding of the groundwater recharge processes are therefore crucial; more so in Nigeria where about half of the landmass is underlain by crystalline rocks (Dada, 1998; Offodile, 2002; NGSA 2009). For these studies, pumping tests are veritable tools for ascertaining aquifer sustainability through reliable estimates of aquifer parameters.

The sole purpose of pumping test is to characterize the hydraulic parameters of the water bearing zone in the subsurface environment by substituting the discharge and the drawdown measurements in the well (or/and piezometers) into an appropriate well-flow equation and calculating the hydraulic characteristics of the aquifer. The choice of a particular test depends on the prevailing hydrogeological conditions, and economic factors. On the strength of these conditions, single-well pumping tests with constant discharge along with the corresponding recovery tests were considered appropriate for hydraulic characterization of basement aquifers of Ibarapa areas. Single-well pumping tests require no piezometer or observation wells, and the constant discharge entails maintaining a uniform pumping rate throughout the period of pumping. Pumping test alone without recovery test back-up are not fully functional for appropriate comprehensive hydraulic studies of basement aquifers. It is always a good practice to measure the residual drawdowns during the recovery period. Recovery-test measurements provide an independent check on the results of the pumping test. It is also less expensive compared to the actual pumping tests. More so, residual drawdown data obtained from recovery tests are more reliable than pumping test data since recovery occurs at a constant rate, whereas a constant discharge during pumping is often difficult to achieve in the field due to fluctuation in yield during pumping. Recovery tests are also useful in terrains where the geo-hydrological attributes are complex and unpredictable, just like that of the crystalline bedrock areas of Nigeria. This is due to abrupt change in lithology and complex structural framework, whereby the groundwater occurrence is erratic and localized in nature (Taylor and Howard, 2000; Offodile, 2002; Van Tonder et al., 2002; Gonthier, 2009;; Akanbi, 2018). Moreover, recovery test is very useful if the pumping test is performed without the use of piezometers (Kruseman and de Ridder, 2000) as was the case in the present work, where single well pumping test was employed for hydraulic characterization of the aquifer system. Additionally, local variations in hydraulic attributes such as groundwater recharge of individual water-bearing zones are intensely measured and accounted for from the residual drawdowns of recovery tests.

The Study Area

The study area for the present study is Ibarapa region. The region is located within the southwestern part of Nigeria, bounded in the East by Ibadan- the capital city of Oyo state, Benin republic at the west, Abeokuta at the south and Oke-Ogun at the North. Presently, Ibarapa region is made up of three political local government areas (LGAs), namely-Ibarapa East, Ibarapa North, and Ibarapa central. The study area covered a total of 709.93 km^2 landmass area of Ibarapa region (Figure 1), on coordinates- 3^0 07’ to 3^o 21’E and 7^0 21’N- 7^0 37’N, covering most parts of both Ibarapa central and Ibarapa north LGAs of Oyo state of Federal Republic of Nigeria. Major township areas within the study area are Igboora, Idere, Ayete and Tapa; with their adjoining communities and villages. The major towns are fairly accessible and are connected by asphalted major road network that linked these areas to bigger towns and cities such as Ibadan, Abeokuta and Iseyin. The adjoining hamlets and villages are however, poorly connected and are mostly accessible by motorcycles and Jeep where the untarred roads are wide enough.

The area lies within the tropical climatic conditions, marked by two distinct seasons of wet and dry seasons. The dry season extends from November to March with an average monthly precipitation of less than 25mm. The wet season peaks around June and September with monthly rainfall exceeding 100 m. The total annual rainfall in the area ranges from 813 to 1853mm, while the annual temperature ranges from 24 to 29 degrees Celsius. When compared to an average rainfall of 1541mm/yr for the entire SW Nigeria, the study area has lower average precipitation and higher average temperature (Munaserei, 1979; Daly, et. al., 1981; David, 1988; Tijani, 2016). Hence, it is expected that the vegetal cover will not be as thick, compared to other parts of SW Nigeria. The vegetal cover is more of derived savannah forested land marked by scattered- scanty small trees and shrubs, sandwiched by tall grasses. It lies between the transition zone of lowland rain forest of southern areas of Nigeria and the savannah zone of the further Northern areas of Oyo state. The vegetation index as groundwater indicator is discussed in latter sections of this work.

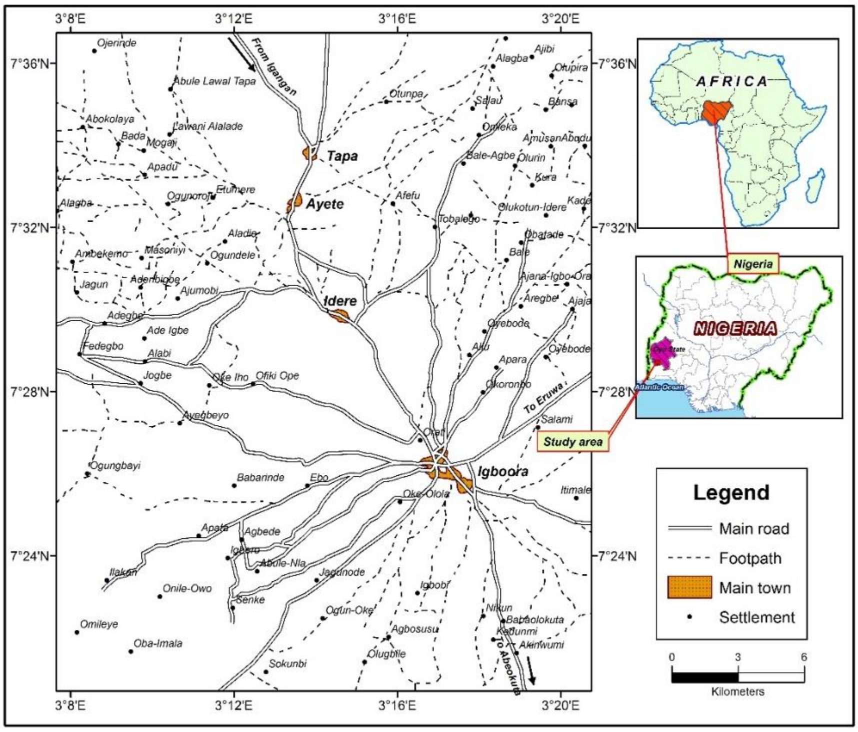

Fig. 1 Location map of the study area

Geology and Drainage

The relief of the study area is sharply undulating characterised by frequent rising and falling in elevations. Figure 2 is a 3 -dimensional illustration of the relief of the area produced from elevation data obtained from the field. The central portion of the area is mainly made up of ridges extending from Igboora to the northern end of the study area with the highlands and intermediate valleys.

The major rock units that underlie the present study area are: porphyritic granite; homogeneous medium grained granite; gneisses which include biotite-hornblende gneiss, biotite-garnet gneiss and augen gneiss; and amphibolites and migmatites. Minor occurrence of porphyroblastic gneiss, quartzites and quartz veins, and pegmatites rock units are also found to be associated with the major rock units in the area. The distribution of the major rock units in the study area is presented in figure 3.

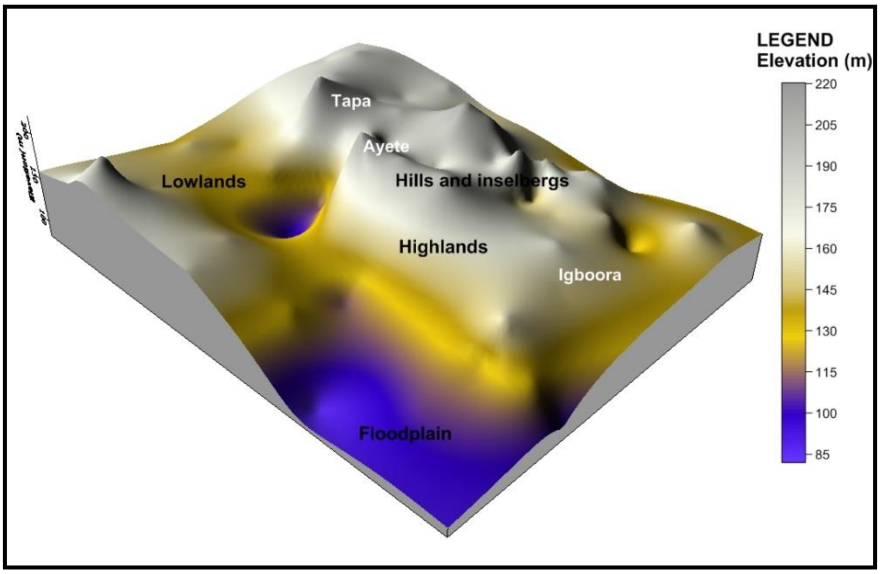

Figure 2 : 3D Surface landform expression, showing the contrast in relief across the study area

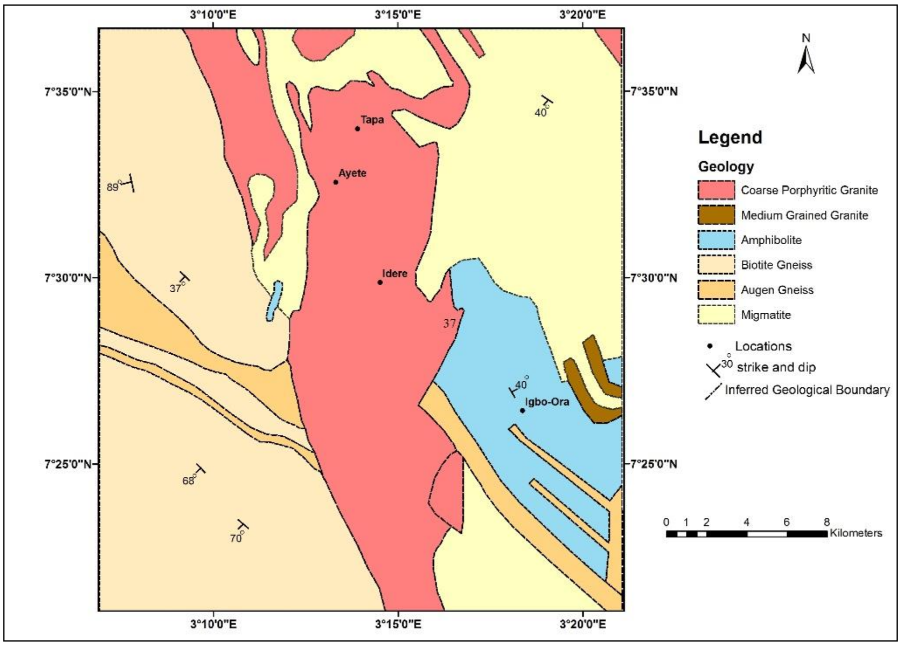

Fig 3: Geological map of the study area

MATERIALS AND METHODS

For the present study, the assessment of aquifer productivity and groundwater recharge entailed the conduct of single well pumping and recovery tests of boreholes within the study areas. The fact that essential aquifer properties such as transmissivity can be reliably estimated from single-well test and that there is no need for observation wells (Kruseman and de Ridder, 2000), makes it suitable for the present study. Aside this, the conduct of single-well test is less cumbersome and relatively less expensive compared to others where drawdowns are monitored from observation wells. An appropriate pumping test should be able to provide data on the immediate hydraulic conditions of an aquifer system being tested from point to point, even within the same bedrock terrain. Hence, due to the expected localized nature of the hydraulic conditions of the bedrock aquifers stemming from the lithological and structural complexities of basement areas of SW Nigeria (Jones, 1985; Akanbi, 2018), including Ibarapa region, and the fact that single-well test can provide essential aquifer properties such as transmissivity of the immediate water-bearing zones, its choice was considered most suitable for the present research. A total of twenty-three wells were tested; seven in areas underlain by amphibolites, six in gneisses, and five each in communities underlain by migmatite and granites (Fig. 4).

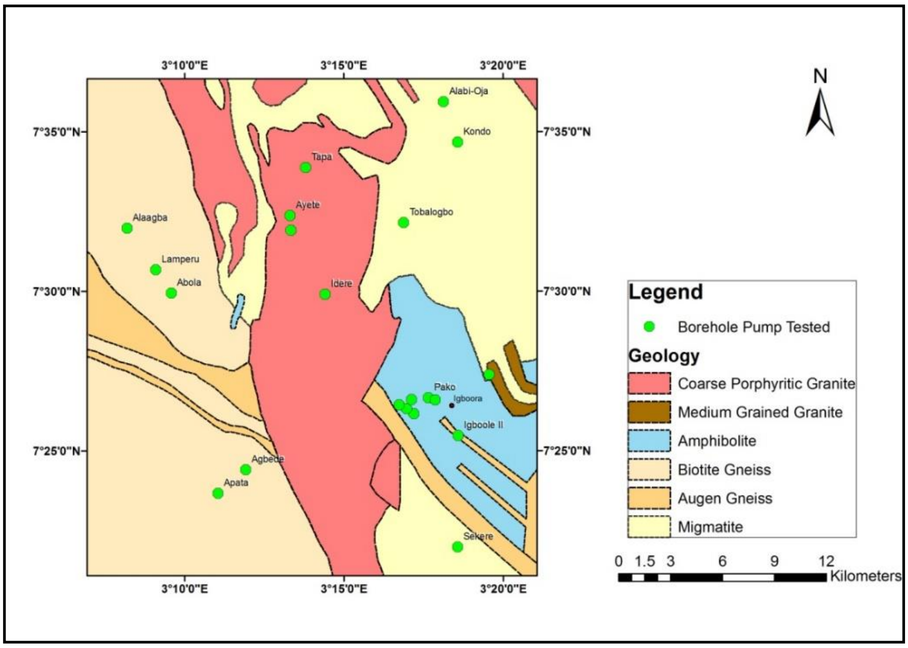

Fig. 4 Locations of tested boreholes on the geological map

Principle and procedures of conducting single-well pumping and recovery tests

Prior to the conducting of the pumping tests, the pre-pumping level, the depth of the well and the saturated column were measured to establish the worth of the boreholes for testing. The field procedures involved the installation of the pump and riser pipes, and field measurements. Water level measurements i.e., drawdowns in the well were taken with depth sounder, while the corresponding volume of water pumped during the pumping test were done using an ISO DN20 water flow meter with accuracy of 0.0001 m^3 (0.1 litre). Precautions were taken to rid the test of backflow of discharged water into the well through direct recharge of discharged water by extending the end of the riser pipes for about 24 feet away from the vicinity of the well and by discharging the released water into the surface concrete drainage network where available. But in most cases, the discharged water was collected by the local people living around the vicinity during testing. The estimable hydraulic parameters from single-well test are the discharge, drawdown, transmissivity and specific capacity of the wells. Other hydraulic properties such as storage coefficient and hydraulic conductivity could not be analysed since no observation well(s) were used in single-well pumping test. The discharge (Q) is the pumping rate and it is the quantity of water discharged per unit time. The unit of the water discharged used in the present study are cubic meter per unit time; where, 1000 liter = $1m^3$. The drawdown is the difference between the water level measured at that particular time and the pre-pumping water level. Residual drawdown on the other hand is the mirror image of drawdown in recovery phase and it is the difference between the water level immediately after the pump is shut down and at a particular time of recovery. The drawdowns were measured in metric unit. Specific capacity was also measured and it is the ratio of the average pumping rate (or discharge) to the total drawdown in the well during the entire pumping period. The unit of specific capacity is m^3/time/m. Other measurable hydrological parameters of interest were the altitude of wells, water table and well depth. These parameters and properties are employable for characterizing the hydraulic attributes of the various bedrock settings of the area.

Analyses of Pumping and Recovery Tests Data

In single-well test the changes in water-level during pumping and recovery period are measured in the well itself, since no piezometer is used. In the hydraulics of well flow, the well is generally regarded as a line source or line sink, i.e., the well is assumed to have an infinitesimal radius so that the well-bore storage can be neglected. The analyses of the pumping and recovery tests involved the measurements of the drawdown and water discharge at specific time intervals during the pumping test phase and corresponding residual drawdowns for recovery tests after pump cessation. Also, plotting the Time- Drawdown on semi-log scales; and estimating the aquifer transmissivity using Jacob's straight-line method (Cooper and Jacob, 1946). Transmissivity, T is estimated from the equation; $T = 2.3Q/4\pi\delta s$; where Q is discharge and δs is the drawdown per log cycle on the time-drawdown curve (Figure 8). Additionally, many methods of analyses of single well pumping tests data based on aquifer type encountered in the field have been designed. For example, the analytical methods of Papadopulos and Cooper (1967), and Rushton and Singh (1983) were designed for analysis of confined aquifers, while Hantush (1964) and Jacob's straight line (Cooper and Jacob, 1946) methods are appropriate for analyzing pumping test data not just from confined but also leaky aquifers.

Groundwater recovery data were used for the estimation of aquifer recharge. Recovery data are more reliable than the drawdown data from pumping tests because the water-table recovers at a constant rate, which is impractical to achieve during the pumping phase in constant discharge tests. The distance between the water level measured during the recovery tests and the pre-pumping level is called the residual drawdown (Fig. 5). The time interval schedule for recovery measurements could be the same as that used during the pumping test; although, the time schedule may vary depending on the rate of recharge. If the recovery is slow, longer time intervals could be used, but when it is rapid, it is advisable to use shorter time intervals at initial stage of recovery which may not correspond to that used during the pumping phase. From the recovery tests conducted along with pumping tests, the residual-drawdown and recovery time were measured to ascertain the rates of groundwater recharge in the aquifers across the various geological settings in the area.

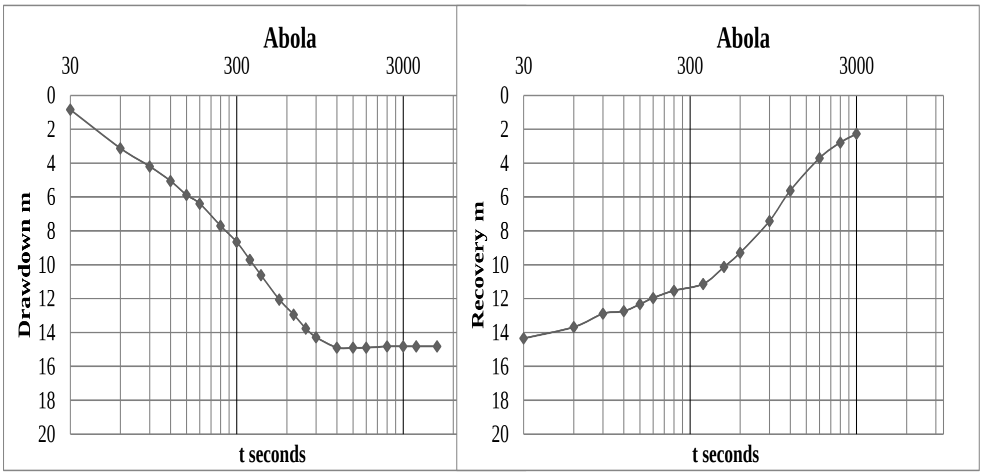

Fig 5 A typical time-drawdown and recovery curve obtained at Abola within the study area

RESULTS AND DISCUSSION

The statistics of well inventory and estimated aquifer properties under various bedrock terrain are presented in Table 1. The altitude of the wells was between 159 and 187m at an average (av.) of 171.6 m above the mean sea level in areas underlain by amphibolites, 139 to 174 (av. 160) m for wells tested in gneisses, 142 to 199 m (av. 180 m) for migmatite and 140 to 215 m (av. 172 m) for porphyritic granite. The corresponding depth of the boreholes were within 18.9 to 38.0 m (av. 27.5m), 30.9 to 99.5 m (av. 46.7 m), 17.8 to 35.6 m (27.7 m) and 15.7 to 36.5 m (av. 25.7 m). Well depths are mostly below 30 m, except in gneisses where the average borehole depth was 46.68 m in the study area. The depth to water-table in amphibolite was 1.46 - 10.70 m (av. 5.60 m), while in gneisses it was between 2.90 to 14.58 m (7.36) m, and 3.34 to 11.83 (5.98) m and 2.00 to 6.48 (av. 3.90 m) for migmatite and porphyritic granite respectively. The discharge (in m^3/day) for wells in amphibolite was between 43.56 and 98.1 (av.72.05), 32.78 to 8.92 (av.53.45) for gneisses, 41.91 to 99.79 (68.27) for migmatite and for porphyritic granite 45.62 to 91.00 (av. 64.33). The total drawdown was 5.20 to 15.36 m (av. 10.70 m), 10.03 to 33.50 (av. 21.99 m), 11.49 to 21.23m (av. 17.69 m), and 7.00 to 22.04 m (av. 15.58 m) respectively. The transmissivities (in m^2/day) ranges are; 0.58 to 11.65 (av. 6.85) in amphibolites; for gneisses, 0.25 to 9.30 (av. 2.57); for migmatite, 0.56 to 0.91 (av. 0.76), and lastly for porphyritic granite 0.56 - 2.95 (av. 1.72). Lastly, the values of specific capacity (in m^3/d/m) were correspondingly; 3.36 to 13.79 (av. 7.67); 1.27 to 7.87 (av. 3.10), 2.25 to 6.05 (av. 4.00); and 2.29 to 10.06 (av. 5.54).

Table 1: Statistics of Hydrological and Hydraulic Parameters by Bedrocks

Bedrock Units	n	Statistics	Well Altitude (m)	Well Depth (m)	Water Table (m)	Q (m^3/day)	Draw-down (m)	T (m^2/day)	Specific capacity (m^3/d/m)
Amphibolite	7	Min.	159.00	18.90	1.46	43.56	5.20	0.58	3.36
		Max.	187.00	38.00	10.70	98.12	15.36	11.65	13.79
		Mean	171.57	27.47	5.16	72.02	10.70	6.85	7.67
		Std. dev.	9.32	6.49	3.00	19.29	3.61	5.53	3.79
Gneisses	6	Min.	139.00	30.90	2.90	32.78	10.03	0.25	1.27
		Max.	174.00	99.50	14.48	78.92	33.50	9.30	7.87
		Mean	160.00	46.68	7.34	53.45	21.99	2.57	3.10
		Std. dev.	15.13	26.20	4.16	19.97	9.30	3.43	2.52
Migmatite	5	Min.	142.00	17.80	3.34	41.91	11.49	0.56	2.25
		Max.	199.00	35.60	11.83	99.79	21.23	0.91	6.05
		Mean	179.80	27.72	5.98	68.27	17.69	0.76	4.00
		Std. dev.	22.00	6.49	3.59	22.33	3.65	0.14	1.50
Porphyritic Granite	5	Min.	140.00	15.86	2.00	45.62	7.00	0.56	2.29
		Max.	215.00	36.50	6.48	91.10	22.04	2.95	10.06
		Mean	172.00	25.70	3.90	64.33	15.58	1.72	5.54
		Std. dev.	37.05	7.95	1.99	17.35	6.91	1.14	4.03

Bedrock and aquifer productivity

The graphical illustrations of variations in the statistics of hydraulic properties are seen in Figure 6. From the average values, groundwater discharge in wells that penetrated amphibolite, migmatite and porphyritic exceeded 60 m^3/day, while those in gneisses have the lowest yield of about 50 m^3/day (Figure 6A). Consequently, the total drawdown during pumping in wells in gneisses is the largest with the mean exceeding 20 m; whereas in other bedrocks, the total drawdowns after pumping were less than 18 m (Figure 6B). Although, this may not necessarily mean that wells in gneisses are less productive. The reason is due to the fact that gneisses are characterised by deeper wells as a result of deeper weathering (Akanbi, 2018). The transmissivities in amphibolites is above 6.0 m^2/day with a range of 0.58 to 11.65m^2/day, followed by gneisses with an average transmissivity above 2.5m^2/day (Figure 6C). The degree of water transmission in migmatite is the lowest with mean transmissivity less than 1.0 m^2/day.

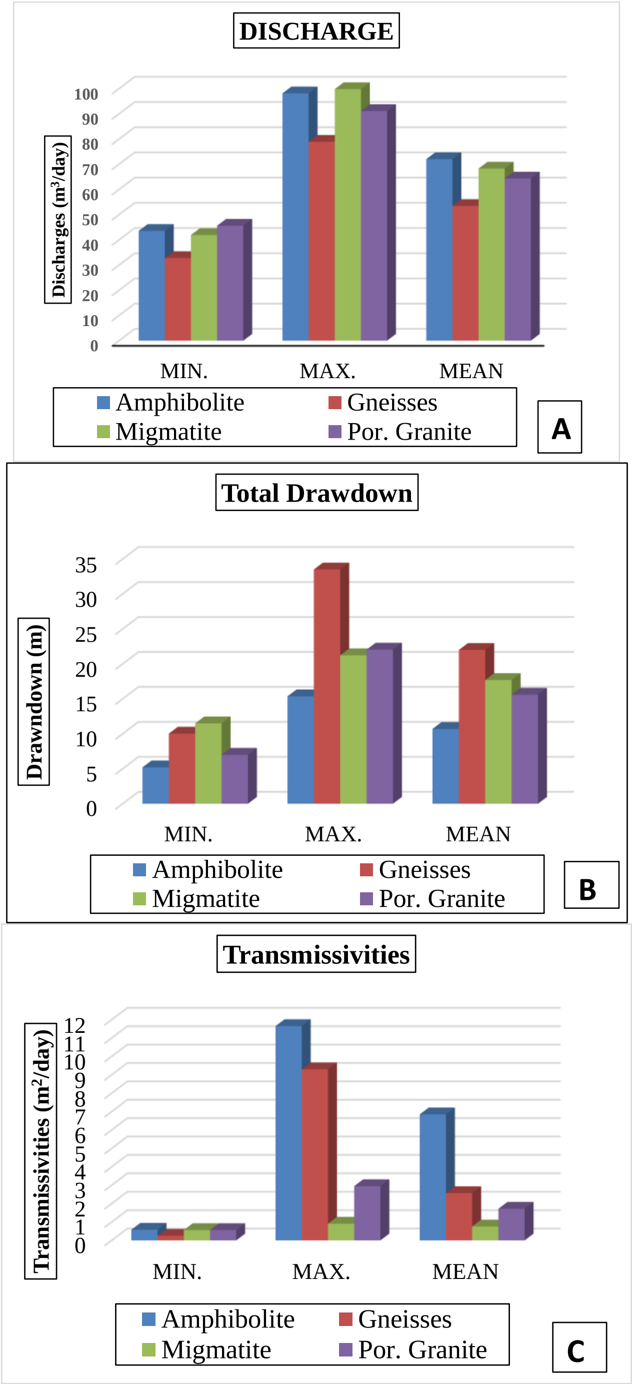

Fig. 6 Histogram illustrations of hydraulic properties by bedrock

Wells tested within terrains underlain by amphibolite have the largest transmissivity of 0.58 to 11.65 m2/day with mean value of 6.85 m^2/day compared to those within other bedrocks terrains (Table 1). Additionally, aside the fact that most wells tested in amphibolite terrain were found prolific, well having the largest transmissivity of 11.65 m^2/day (at Ajegunle) along with other three wells having more than 10 m^2/day transmissivities were found within locations underlain by amphibolite. Hence this bedrock can therefore be regarded as the bedrock that has the highest potential for provision of prolific wells in the study area.

A total number of six (6) wells were tested within areas underlain by gneisses. The two wells located at Alaagba and the one tested at Lamperu have transmissivities ranging from 0.25 to 0.65 m^2/day (Table 1). Wells at Abola and Apata were characterised by less prolific water-bearing bedrock with transmissivities of 2.13 and 1.54 m^2/day respectively. The well at Agbede, is characterised by high-yielding bedrock with transmissivity of 7.23 m^2/day. All the five boreholes tested in migmatite bedrock terrains were associated with large drawdowns during pumping at an average value~~s~~ of 17.69 m. The large drawdown signifies low groundwater yield. Among other bedrocks that underlain the study area, the water bearing zones in migmatite terrain have the lowest transmission capacity with the transmissivities ranging between 0.56 and 0.91 m^2/day (av. 0.76 m^2/day). Wells in granitic bedrock terminate on fresh basement, or on a network of unconnected (or dry) fractures. Notably, in granitic bedrock, weathering and bedrock fracturing are least developed (Akanbi, 2018). Hence, large groundwater yield is not sustainable within this bedrock terrain; except at Ayete I. This well penetrated fractured bedrock. Though, the yield of the well is low, the water flows for hours and throughout pumping phase. This is because the borehole at Ayete I is sited in valley incision of the granitic ridges. The low elevation attribute creates lower hydraulic or pressure head that guarantees water influx from higher grounds. The coarse (sandy) regolith unit associated with granitic terrains aids good water transmission in that area. most other wells in granitic terrains were characterized by large drawdown and low yield. Occurrences of more successful boreholes in amphibolite and gneisses were partly due to the hydro-geomorphic situations, whereby water is drained from the high-lying areas that are mainly underlain by migmatite and porphyritic granite and discharge to the low - moderately lying regions of amphibolite and gneisses terrains (Akanbi, 2018). Hence, migmatite and granitic terrains are more of run-off zones, whereas most terrains underlain by amphibolite and gneisses bedrock are the discharge zones.

Out of all the tested wells, a total number of eight (8) wells, namely those located at Ajegunle, Igboole II, Igboole I, Pako, Agbede, Ayete I, Abola and Apata with transmissivities of 2.02 – 11.65 (av. 7.75) m2/day are regarded as prolific and sustainable (Figure 7). This is as a result of long pumping time, small drawdown, and attainment of dynamic water level during pumping period. Each of these wells terminate on recharge boundary that is either a fractured or weathered bedrock. The first four locations having the largest transmissivities with corresponding values of 11.65, 11.56, 11.52, 10.34 and 9.30m^2/day are located within amphibolite terrains, while those at Agbede, Abola and Apata are underlain by gneisses. Ayete I is the only prolific well tested within porphyritic granite terrains. The depths of these prolific wells were mostly within the range of 30 to 38 m, except the one at Ajegunle that has a depth of 18.9 m. The average depth for these prolific wells is 31.7 m and are mostly found in terrains underlain by amphibolites and gneisses.

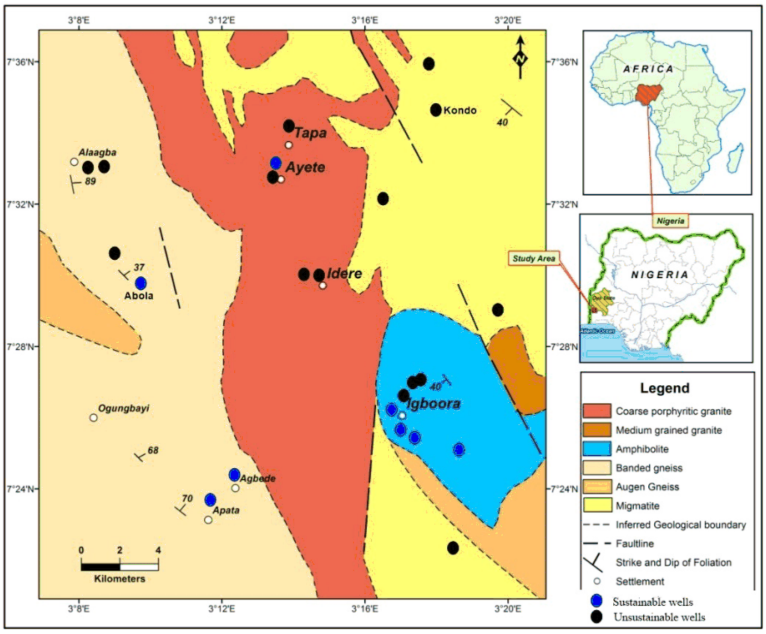

Fig. 7 Locations of prolific and low-yielding wells on geological map

Groundwater recovery and sustainability

The residual drawdown and total recovery time measured in the wells are presented in Table 2, while the statistics of recovery parameters in bedrocks are presented in Table 3. The total recovery time spread from as short as ten (10) minutes for borehole at Agbede, to as long as 171 minutes at Alaagba. The average recovery time for all the boreholes was about 68 minutes and the rate at which water rises in the wells was 0.25 meter/minute (Table 2).

The residual drawdown which is the length at which water filled the wells during recovery period ranged between 4.60 and 22.88 m while the mean was 13.40 m. The total recovery time for the wells to recover was between 10 and 171 minutes (av. 67.9). From the average values of these two parameters (Table 2), it can be deduced that it took about 68 minutes for water to rise by 13.4 m in an average borehole in the study area. Based on the average values, the rates of recovery in each geological terrain as presented in Table 3 showed that wells in amphibolites and migmatite areas recovered at similar rates of 0.23 meter/minute compared to 0.33 meter/minute in gneisses and 0.21 meter/ minute in granitic terrain. The plots of transmissivity of the aquifers versus recovery time is indirect and fairly significant (Figure 8) typifying that good water transmission in the aquifer will reduce the rates of recovery that means good water recovery in the well. The good transmission in granitic aquifers is however not sustainable over long period of pumping as compared to those wells in amphibolites and gneisses terrains where the transmissivities were higher (Table 3) as a results of sustainable groundwater yield over long period and development of dynamic -equilibrium water level

Table 2: Residual drawdowns and groundwater recovery time

Sn.	Borehole Location	Total residual-drawdown, (meter)	Total recovery time (Minutes)	Groundwater Recovery rate Meter/ minute	Transmissivity m^2/day	Specific capacity (m^3/d/m)
1	Onilado	12.76	60	0.21	0.58	3.36
2	Sagaun	13.85	60	0.23	1.28	6.39
3	Pako	7.65	60	0.13	10.34	9.27
4	Igboole I	4.60	60	0.08	11.52	13.83
5	Igboole II	12.37	40	0.31	11.56	5.03
6	Ajegunle	7.02	40	0.18	11.65	11.01
7	Itaagbe	11.34	25	0.45	1.03	4.87
8	Alaagba I	13.05	171	0.08	0.25	1.27
9	Alaagba II	22.88	100	0.23	0.52	1.64
10	Lamperu	17.80	80	0.22	0.65	3.93
11	Abola	12.55	50	0.25	2.68	2.21
12	Apata	14.53	50	0.29	2.02	1.69
13	Agbede	8.81	10	0.88	9.3	7.87
14	Sekere	17.10	120	0.14	0.88	4.12
15	Tobalogbo	10.57	60	0.18	0.91	6.05
16	Kondo	14.77	60	0.25	0.71	2.89
17	Alabi-Oja	18.17	44	0.41	0.56	2.25
18	Apata-Faju	21.05	110	0.19	0.73	4.70
19	Idere I	8.09	120	0.07	2.94	9.83
20	Idere II	6.83	50	0.14	1.19	10.06
21	Ayete I	17.00	76	0.22	2.95	2.88
22	Ayete II	14.05	60	0.23	0.56	2.29
23	Tapa	21.88	55	0.40	0.96	2.62
	Minimum	4.60	10.0	0.07	0.25	1.27
	Maximum	22.88	171.0	0.88	11.65	13.83
	Mean	13.40	67.9	0.25	3.29	5.22

Table 3: General statistics for the phases of groundwater recovery and specific capacity of wells in various bedrocks

Bedrock Units	n	Statistics	Residual draw-down (m)	Recovery time	Rate of recovery in wells Meter/minute	Transmissivity m^2/day
Amphibolite	7	Min.	4.60	0.62	0.08	0.58
		Max.	13.85	3.68	0.45	11.65
		Mean	9.94	1.84	0.23	6.85
		Std. dev.	3.50	1.01	0.12	5.53
Gneisses	6	Min.	1.27	0.62	0.08	0.25
		Max.	22.88	7.14	0.88	9.30
		Mean	14.94	2.63	0.33	2.57
		Std. dev.	4.86	2.28	0.28	3.43
Migmatite	5	Min.	10.57	1.15	0.14	0.56
		Max.	21.05	3.35	0.41	0.91
		Mean	16.33	1.89	0.23	0.76
		Std. dev.	3.93	0.87	0.11	0.14
Porphyritic Granite	5	Min.	6.83	0.55	0.07	0.56
		Max.	21.88	3.22	0.40	2.95
		Mean	13.57	1.72	0.21	1.72
		Std. dev.	6.26	1.01	0.12	1.14

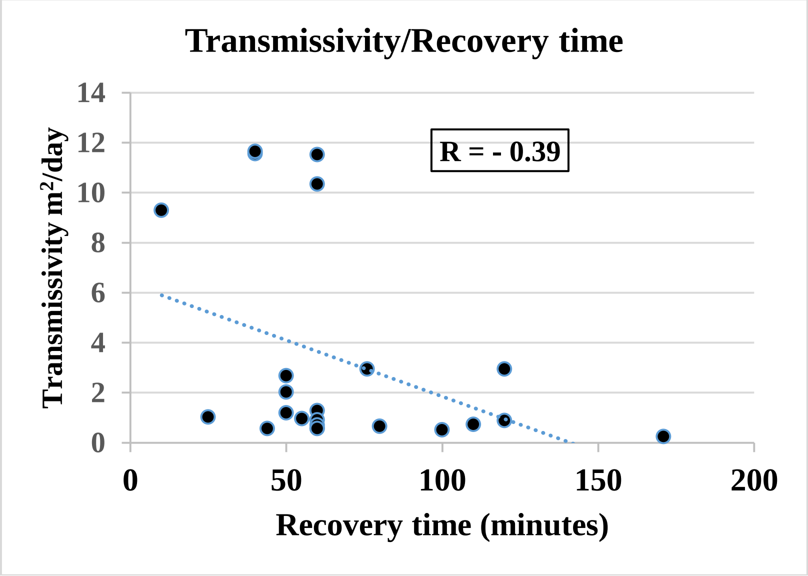

Fig. 8 Plots of transmissivity against groundwater recovery in the wells

CONCLUSION

Water levels in prolific wells exhibited dynamic equilibrium level, whereby the drawdown stabilized during pumping operation. The incidence of these wells in the study is eight, which represents about 35% of all the tested wells. These wells were regarded as being sustainable and prolific, and were mostly associated with terrains underlain by amphibolites and gneisses with just one on granitic terrain at Ayete 1. Additionally, these wells were also characterized by high specific capacity. On the other hand, all the wells marked as unsustainable were characterized by reducing pumping rates, whereby discharge is not sustainable, this led to water cessation during pumping operations. Many of these wells were characterized by large water discharge at the early pumping time, the discharge drastically falls as pumping operation continues. This is a clear case of well-bore storage effect, whereby water storage in the well leads to initial good yield, which declines with time, hence, the initial good yield does not represent the actual aquifer yield. Generally, the yield of water bearing zones in areas underlain by granite and migmatite are low and could not sustain a continuous water discharge for hours. Nonetheless, productive wells are encountered in amphibolite terrains and can guarantee a sustainable groundwater yield for the entire region.

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