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Well and Formation Losses in Boreholes Constructed in a Weathered Crystalline Basement Aquifer in Nigeria

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Abstract: In this paper, we present the results of a study on well and formation losses in three new public water supply boreholes drilled in a weathered granitic aquifer in Nigeria using data obtained from step drawdown tests conducted to assess the potential yields of the wells.

Our results show a mean yield of 2.93 l/s for the three wells and this compares with values reported for similar formations in other regions of the world. Well losses increased with pumping rates for individual wells and contribute between 5.2% and 70.54% of the total drawdown of the wells studied. Recommendations for minimizing well losses and hence total pumping costs are made.

Key words: Boreholes, weathered basement, well loss, formation loss, hydrogeology, well development, pumping test, yield.

Introduction

It has long been realized that the provision of clean water improves health and quality of life (Herbert, 1981). Other benefits of improved water supply include high productivity and socio-economic developments (Mustafa and Yussuf, 1999). If these benefits and improvements are to be sustainable, the water source or scheme must not only be socially acceptable and environmentally friendly, there must also be a reliable operation and maintenance system.

In many areas of the world, particularly in arid and semi arid regions of developing countries, the borehole is the only available source of useful potable water (Rofe, 1980). Hence the construction of efficient water wells is fundamental to any programme of social and economic progress in these regions.

With groundwater coming under increasing threats from growing demand, wasteful use and contamination, the search for additional water sources, particularly in developing countries, have extended to less favourable areas like crystalline basement aquifers (weathered igneous and metamorphic rocks).

Igneous and metamorphic rocks are at or near the surface in more than 20% of the land surface of the world (Davis and Dewiest, 1966) and about one third of the developing world. Basement complex hydrogeological province occupies nearly half and most of the central area of Nigeria (Offodile, 2000). This underscores its importance in the water resources development of the country in spite of their poor hydrogeological properties.

The poor hydrogeological properties of fresh metamorphic and igneous rock is due mainly to the fact that they have typical porosities of less than 3% and most commonly less than 1% with the few pores present being small and often not interconnected resulting in very low permeabilities which can be regarded as zero in most practical cases.

Failures of boreholes constructed in crystalline rocks of southwestern Nigeria have been attributed to the following causes (Ajayi and Abegurin, 1990):

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(i) Seasonal variation in water level
(ii) Improper casing
(iii) Pumping failures
(iv) Poor siting and non-penetration
(v) Poor completion

In many developing countries most boreholes are put into operation after well development without any form of pumping test to assess the potential yield of the water source before pumps are installed. The reason often adduced for this unsustainable practice is lack of funds or finance and required technical expertise. The global rising trends in energy cost and declining water tables in major aquifers which causes additional pumping lift and consequent increase in the total pumping costs have made minimizing water level drawdown an important consideration in the design, construction and operation of municipal water wells.

With modern geophysical techniques and better understanding of basement aquifers which now allows more efficient siting of sources of water (Herbert, 1981), water level drawdown and hence pumping cost can be minimized in well constructed boreholes in these formations by minimizing loss of head at the borehole/formation interface.

In this paper, we present the results of the study of well and formation or aquifer losses in three public supply boreholes drilled, completed and pump tested under similar conditions in the semi-urban North Eastern Nigeria town of Tafawa Balewa.

The study objectives are:

1. To identify how much of the total head loss in each of the study wells in the field is attributable to natural losses in the formation (aquifer loss) and those caused by well construction damage to the aquifer and the installation of screen and filter packs.
2. To find the abstraction limit of the wells and the rate at which water level falls with time.

These objectives will enhance the sustainable management of the wells.

The Study Area

Climate and General

The study area, Tafawa Balewa town is in Bauchi state Nigeria located between latitudes 9°-13° North and longitude 9°-12°E.

Tafawa Balewa is the administrative headquarters of Tafawa Balewa local government council area of Nigeria. The town has a projected population of 14,320 in 2004 using 3% annual growth rate on the last population census of 9750 in 1991.

Tafawa Balewa falls under the Northern Guinea Savannah zone with annual rainfall ranging from 1000 mm to 1500 mm.

The average mean monthly temperature varies from 15°C to 35°C.

Geology and Hydrogeology

Bauchi state falls under the North Eastern Nigeria characteristic geological formation comprising both of sedimentary formation and quaternary to upper cretaceous ages and undifferentiated basement complex and the stratigraphic succession of the region is composed of alluvium Chad formation, Keri keri formation and crystalline basement complex (Dar, 1991).

Specifically, the geology of Tafawa Balewa area is characterized by a succession of lateritic reddish soil with clay, weathered basement material of biotite granite origin (Offodile, 2000). The weathered basement complex is underlain by basement complex.

The basic factors, which govern the hydrogeologic characteristics of crystalline rocks, include lithology, structure climate and weathering (Ajayi and Abegurin, 1990). The lithologic logs at the location of the three boreholes are shown in Tables 1 to 3.

Table 1: Lithology at the Location of Borehole TB01*

Thickness	*Sample description*
0-3.5 m	Lateritic soil, reddish
3.5-6.0 m	Gravel and coarse sand, whitish
6.0-11.0 m	Sandy with clay reddish medium grain
11.0-17.0 m	Granitic rock
17.0-29.0 m	Sand, fine to medium grained hard, some clay
29.0-36.0 m	Sand, fine to medium gravel weathered materials
36.0-61.0 m	Weathered basement materials fine to medium grained, iron stained, greyish black spots.
61.0-65.0 m	Hard rock.

*NWRP Report, 1997.

Basic Theory of Formation and Well Losses in Pumped Wells

The efficiency of a pumping well is expressed quantitatively by identifying and determining the separate components of total draw- down S_i in the form (Johnson and Rushton, 1981):

$$S_i = S_a + S_w \tag{1}$$

where S_a is the part of the drawdown due to aquifer loss while S_w represents the part due to well losses.

Table 2: Lithology at the Location of BH TB02*

Thickness	*Sample description*
0-2.5 m	Lateritic soil, reddish
2.5-13.0 m	Granitic rock
13.0-26.0 m	Weathered materials fine to medium grained, dark greyish
26.0-29.0 m	Weathered basement materials compacted
29.0-66.0 m	Weathered basement material fine to medium grained greyish white with blackish spots
66.0-70 m	Weathered basement material fine to medium grained compacted greyish white with black spots
70-76 m	Weathered basement material medium grained, greyish white with blackish spots
76.0-79.0 m	Fresh basement rock

*NWRP Report, 1997.

Table 3: Lithology at the Location of BH TBO3*

Thickness	*Sample description*
0-6.0 m	Lateritic soil, reddish
6.0-16.0 m	Fine silty sand and clay, darkish grey, iron stained
16.0-29.0 m	Weathered materials, medium to coarse-grained dark greyish.
29.0-39.0 m	Weathered basement material, fine to medium grained, blackish spots, greyish
39.0-59.0 m	Weathered basement material, fine to medium grained, greyish white
59-60.0 m	Fresh basement rock

*NWRP Report, 1997.

Aquifer loss represents the inevitable loss of head due to laminar flow of water through the aquifer, while well losses are a function of non-linear flow within the well and the immediate adjacent part of the aquifer.

In a 100% efficient well, there are no well losses so $S_i = S_a$. This is a theoretical ideal that is rarely attainable for practicable abstraction rates. Hence it is often necessary to express the efficiency of a well in terms of a percentage of the theoretical maximum. Jacob (1947) derived the equation

$$S_i = BQ + CQ^n \quad (2)$$

where B and C are the aquifer and well loss constants respectively, Q is the prevailing pumping rate and n is a variable exponent. Jacob suggested a value of 2 for n, hence the equation above becomes

$$S_i = BQ + CQ^2 \quad (3)$$

The graphical solution for separating the drawdown is by plotting the specific discharge $\left(\frac{S_i}{Q}\right)$ against Q

C is the slope of the line of best fit through the data points while B is the intercept of the line on the specific discharge $\left(\frac{S_i}{Q}\right)$ axis.

Where the choice of $n = 2$ fails to produce satisfactory result, the method of analysis proposed by Rorabough (Izinyon, 1997) in which C is determined by trial and error is adopted.

Methodology and Test Procedure

The three boreholes studied in this paper are sited in a well field located some 500 metres away from the centre of town as geophysical investigation concentrated within the town to minimize cost of transmission pipelines did not yield positive results.

Five wells drilled previously during this exercise without any geophysical investigation resulted in boreholes that were abortive. The three boreholes were drilled, completed and pump tested using same procedure and under similar conditions. Pumping tests (step drawdown and recovery test) were conducted on each of the study boreholes.

Pumping Tests (SDDT and Recovery)

Step drawdown test (SDDT) was conducted on each well at four successive discharge rates (25%, 50%, 75% and 100%).

In each of the four stages, the wells were pumped for 2 hours duration at successive minutes; one minute each for the first ten minutes, two minutes each for the next ten minutes, five minutes each for the next 40 minutes and then ten minutes each for the next one hour. The step drawdown test was immediately followed by well recovery test. In the well recovery test, recovery to static water level was measured every 30 seconds for the first five minutes and thereafter every minute until the water level rose to the static water level.

Test Equipment

The equipment used for the pumping test include

(i) Electric water level sounder
(ii) Grundfos submersible pumps (various capacities)
(iii) Generator
(iv) Stop watch
(v) Tank of known volume (200 litres/100 litres)

The discharge from the pumped well was measured by noting the time taken to fill the tank of known volume. The discharge for each stage was maintained at constant rate by means of a gate valve fitted on the open discharge pipe. Precaution was taken to ensure that the discharge is conducted away from the area of the pumped well.

Results and Discussion

Table 4 (a): Particulars of Study Boreholes*

BH No.	*BH diameter (mm)*	*Drilled depth (m)*	*SWL (m)*	*Screen length (m)*	*BH yield*	*Pump intake (m)*
TB01	150	65	3.80	40.18	2	62
TB02	150	79.5	3.63	42.0	1.8	77
TB03	150	60	5.0	39	5	38

*NWRP Report and Izinyon, 1997.

Table 4 (b): SDDT Data for the Boreholes*

Sl. No.	*BH No.*	*Step*	*Q (m^3/d)*	*Drawdown, S_i (m)*
1.	TB01	1	43.2	5.51
		2	86.4	12.38
		3	129.6	19.38
		4	172.8	25.86
2.	TB02	1	38.88	4.44
		2	77.76	11.52
		3	116.64	21.02
		4	155.52	37.21
3.	TB03	1	81	1.52
		2	162	3.58
		3	324	5.63
		4	432	10.54

*NWRP Report and Izinyon, 1997.

Table 4 (c): Variation of Drawdown with Steps of Discharge

Sl. No.	*BH No.*	*Step*	*ΔQ (m^3/d)*	*ΔS_i (m)*
1	TB01	1	43.2	5.51
		2	43.2	6.87
		3	43.2	7
		4	43.2	6.48
2	TB02	1	38.88	4.44
		2	38.88	7.08
		3	38.88	9.50
		4	38.88	16.19
3	TB03	1	81	1.52
		2	81	2.06
		3	81	2.05
		4	81	4.91

Table 5: Specific Capacity Discharge Data for the Boreholes

BH No.	*Step*	*Q (m^3/d)*	*Drawdown (m)*	*Specific capacity $m^3/d/m$*	*Specific drawdown (S/Q) ($m/m^3/d$)*
TB01	1	43.2	5.51	7.84	0.1275
	2	86.4	12.58	6.868	0.1495
	3	129.6	19.38	6.687	0.1495
	4	172.8	25.86	6.682	0.1497
TB02	1	38.88	4.44	8.757	0.1142
	2	77.76	11.52	6.750	0.1481
	3	116.64	21.02	5.549	0.1802
	4	155.52	37.21	4.160	0.2400
TB03	1	81	1.52	53.29	0.0188
	2	162	3.58	45.25	0.0221
	3	324	5.63	57.55	0.0173
	4	432	10.54	40.99	0.0244

Table 6: Aquifer and Well Loss Constants for the Boreholes (Obtained Graphically)

BH No.	*Aquifer constants B (d/m^2)*	*Well loss constants C (d^2/m^5)*
TB 01	1.256×10^{-1}	1.6226×10^{-4}
TB02	6.824×10^{-2}	1.053×10^{-3}
TB03	1.859×10^{-2}	1.408×10^{-5}

Tables 1, 2 and 3 show the lithology at the locations of the three boreholes in the well field. The wells have yields of 2 l/s, 1.8 l/s and 5 l/s respectively.

The difference in well yields is more likely to be due to the degree of weathering rather than inherent differences in the mineralogy or fabric within the rock. This underscores the need for proper investigation before wells are sited in this locality.

Table 4 (a) shows the particulars of the study wells: the drilled depth for the boreholes TB01, TB02 and TB03 are 65 metres, 79.5 metres and 60 metres respectively while their yields are 2 l/s, 1.8 l/s and 5 l/s respectively.

Table 4 (b) presents the summary of the step drawdown test data for the wells. Table 4 (c) shows how the drawdown varies during each constant step for the three wells. For boreholes TB01, the change in drawdown varies from 5.51 m in step 1 to maximum of seven metres in step 3.

For borehole TB02, the drawdown varies from 4.4 metres in step 1 to 16.19 metres in step 4.

In borehole TB03, the change in drawdown varies from 1.52 metres in step 1 to 4.91 metres in step 4.

Table 7: Computation of Aquifer and Well Losses for the Boreholes

BH No.	*Step*	*Discharge Q (m^3/d)*	*Drawdown S (m)*	*Specific drawdown (m/m^2/d)*	*Aquifer loss constant (B)*	*Well loss constant (C)*	*Formation loss, BQ (m)*	*Well loss CQ^2 (m)*	*Total drawdown BQ+CQ^2 (m)*	*% Deviation from measured drawdown*
TB01	1	43.2	5.51	0.1275	0.1256	0.000162	5.508	0.302	5.81	5.4%
	2	86.4	12.58	0.1475	0.1256	0.000162	11.02	1.209	12.23	2.78%
	3	129.6	19.38	0.1495	0.1256	0.000162	16.52	2.721	19.24	0.72%
	4	172.8	25.86	0.1497	0.1256	0.000162	22.03	4.837	26.86	3.86%
TB02	1	38.88	4.44	0.1142	0.0682	0.00105	2.6522	1.587	4.239	4.52%
	2	77.76	11.52	0.1481	0.0682	0.00105	5.303	6.349	11.652	1.15%
	3	116.64	21.02	0.1802	0.0682	0.00105	7.955	14.285	22.24	5.8%
	4	155.52	37.21	0.2400	0.0682	0.00105	10.606	25.395	36.00	3.25%
TB03	1	81	1.52	0.0188	0.0186	0.0000141	1.506	0.0925	1.598	5.13%
	2	162	3.58	0.0221	0.0186	0.0000141	3.013	0.3700	3.383	5.50%
	3	324	5.63	0.0173	0.0186	0.0000141	6.026	1.480	7.506	33.3%
	4	432	10.54	0.0244	0.0186	0.0000141	8.035	2.631	10.666	1.19%

Table 8: Separation of Formation and Well Loss Components of Drawdown

BH No.	*Step*	*Discharge Q (m^3/d)*	*Formation loss (m) BQ*	*BQ in % of total loss*	*CQ^2(Well loss) (m)*	*CQ^2 in % of total loss*	*Theoretical total drawdown (m)*
TB01	1	43.2	5.508	94.80	0.302	5.2	5.81
	2	86.4	11.02	90.1	1.209	9.9	12.23
	3	129.6	16.52	85.86	2.721	14.14	19.24
	4	172.8	22.03	82.02	4.837	17.98	26.86
TB02	1	38.88	2.652	62.56	1.587	37.44	4.239
	2	77.76	5.303	45.5	6.349	54.5	11.652
	3	116.64	7.955	35.77	14.285	64.23	22.24
	4	155.52	10.606	29.46	25.395	70.54	36.00
TB03	1	81	1.506	94.24	0.0925	5.76	1.598
	2	162	3.013	89.06	0.3700	10.94	3.383
	3	324	6.026	80.28	1.480	19.72	7.506
	4	432	8.035	75.33	2.631	24.67	10.666

Table 9: Variation of Formation and Well Losses with Discharge

BH No.	*Step*	*Q (m^3/d)*	*Formation loss (%)*	*Well loss (%)*
TB01	1	43.2	94.80	5.20
	2	86.4	90.10	9.90
	3	129.6	85.86	14.14
	4	172.8	82.02	17.98
TB02	1	38.88	62.56	37.44
	2	77.78	45.50	54.50
	3	116.64	35.77	62.23
	4	155.52	29.46	70.54
TB03	1	81	94.24	5.76
	2	162	89.06	10.94
	3	324	80.28	19.72
	4	432	75.33	24.67

Table 4 shows the specific capacity of the wells, which is a measure of the performance of the boreholes. The specific capacity of the wells decreased generally with increase in discharge for the operating range of the individual wells. Though the highest values of specific capacity indicates best performance, and hence optimum rate of abstraction quite often demand requirements dictate otherwise.

Table 6 presents the values of aquifer loss constants (B) and well loss constants (C) for the wells obtained graphically from the plots of (S_i/Q) against Q shown in Figures 1, 2 and 3.

Aquifer loss constants (B) is the intercept on the (S_i/Q) axis while C is the slope of the straight line.

The value of B and C for each well is used to compute the corresponding aquifer and well loss component of the total drawdown.

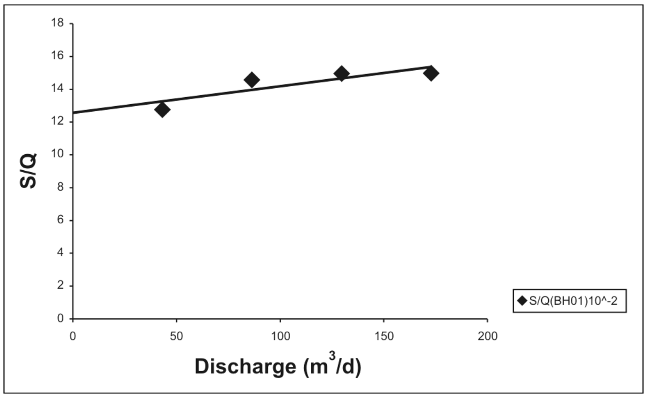

Figure 1: Graphical determination of aquifer and well loss constants for BH 01.

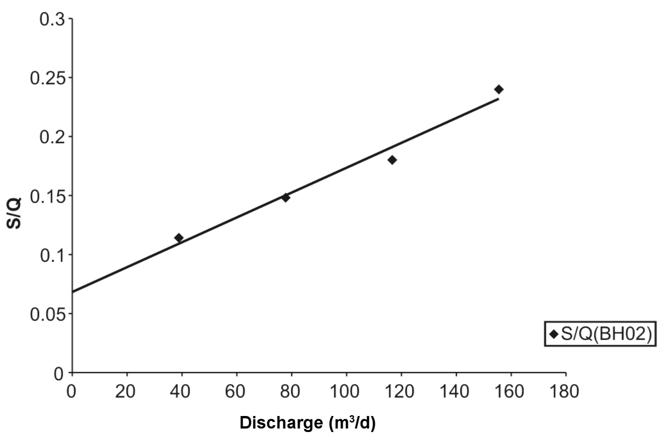

Figure 2: Graphical determination of aquifer and well loss constants for BH 02.

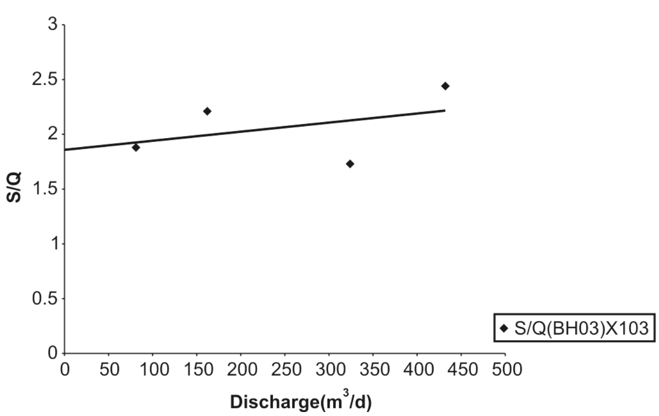

Figure 3: Graphical determination of aquifer and well loss constants for BH 03.

The deviation of theoretical drawdown from the measured drawdown varies from 0.72% to 5.4% in TB01, 1.15% to 5.8% for well TB02 and 1.19% to 33.3% for TB03.

Table 9 shows the separation of the formation and well losses in percentages of the total drawdown with a view to seeing the relative contribution of each to the total drawdown at each stage in the study boreholes. The table reveals that well losses contribute between 5.2% and 17.98% of the total drawdown in the four stages in the case of TB01. In Borehole TB02, well losses contribute between 37.44% and 70.54% of the total drawdown. The mean for the four steps is 55.35%.

In Borehole TB03, well losses contribute between 5.76% and 24.67% of the total drawdown. The mean for the four steps is 15.27%.

As can be seen in Figures 4, 5 and 6, well losses increased with increase in discharge within the operating range of the well. It is observed that well TB02 is most inefficient of the three wells; this is probably due to inadequate well development or design.

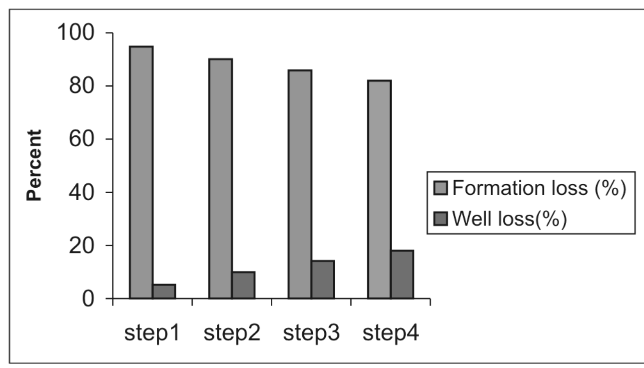

Figure 4: Formation and well losses in TB01.

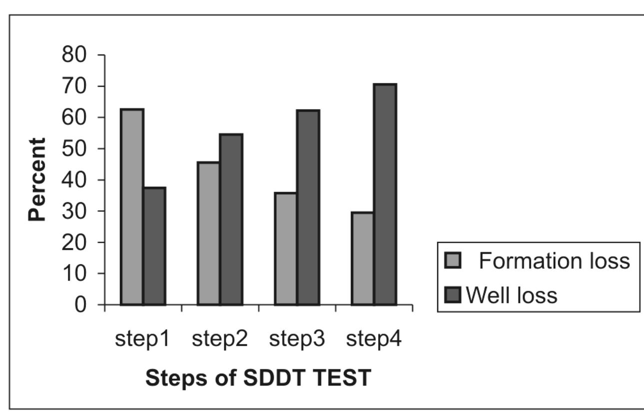

Figure 5 : Formation and well losses in TB02.

This is noted for the operation stage of the borehole, and calls for closer maintenance attention and monitoring to increase the service life of the well.

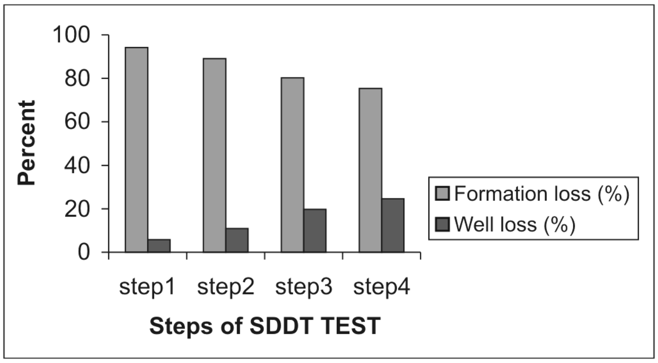

Figure 6 : Formation and well losses in TB03.

Conclusions

The following conclusions are made

(i) That geophysical investigation be carried out before siting of water wells in crystalline basement rocks in order to reduce the incidence of abortive or low yield wells in these formations.

(ii) That the mean yields of the wells studied is in good agreement with those reported for similar formations in other regions of the world.

(iii) That well losses can be a major component of the total drawdown encountered in pumped wells in weathered basement aquifers. This can however be minimized by adequate well development and design to save on the operation and maintenance costs of the wells in addition to increased service lives. This is particularly important in sub-Saharan Africa where per capita income is low, access to potable water is limited and poverty level is high.

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