Characterisation of weathered and granitised fractured bedrock aquifer based on WISH and FC methods

Jacob Nyende[1*], van Tonder G[2] and Danie Vermeulen[2]
[1]*Department of Civil & Building Engineering, Faculty of Engineering, Kyambogo University, PO Box 1, Kyambogo-Kampala, Uganda*
[2]*University of the Free State, Institute for Groundwater Studies, Faculty of Natural and Agricultural Sciences, PO Box 339, Bloemfontein 9300, South Africa*

Abstract
The hydrodynamic properties of the weathered-fractured layer of a hard-rock in a granitic terrain are characterized using hydraulic tests at different scales in Pallisa District. The WISH and FC methods used required short-duration pumping cycles on an unconfined aquifer with differing seasonal water-table fluctuations. The interpretations of several pumping tests at a site in Pallisa District under various initial conditions provide information on the change in hydrodynamic parameters in relation to water-table level. The transmissivity linearly decreases compared with the available water level, suggesting a non-homogeneous distribution of hydraulic conductivity with depth. The hydraulic conductivity is estimated from the slope of this linear relationship .The extrapolation of the relationship between transmissivity and water level provides an estimate of the aquifer thickness that is in good agreement with geophysical investigations. The hydraulically active part of the aquifer is located in both the shallow weathered and the underlying densely granitic fractured zones of the crystalline basement. It appears that the extension of the most conductive part of the weathered-fractured layer is limited down to 50 metres depth. However, no significant relationship is found between the aquifer storage coefficient and water level. These methods contribute to filling the methodological gap between single pumping test and hydraulic tomography, in providing information on the variation of the regional transmissivity according to depth. They can be applied to any unconfined and semi-confined aquifers that experience seasonal water-table fluctuations and short pumping cycles.

Keywords: groundwater hydraulics, Pallisa District, crystalline rocks, granitic fractured rocks, pumping tests

Introduction
Crystalline rocks such as granites are usually devoid of primary porosity. Secondary porosity is developed due to weathering and fracturing of the granitic rock. These weathered and fractured rocks form aquifers where occurrence and flow of groundwater takes place. The presence and flow of groundwater in such formations mainly depends on (1) the saturated thickness of the weathered zone and (2) the intensity and areal extent and interconnection of joints and fractures in the granitic rock. It has been determined by [1] that generally the yield in such granitic formations decreases with depth which is mainly due to a decrease in the degree of fracturing with depth. Thus, most of the groundwater circulation restricts to shallow depths. In a detailed study, [1] found the optimal depth of maximum yield in a weathered and fractured granitic terrain as 23 - 30 m. Further, [2, 3] and [4] determined that there is a significant variation in the yield between nearby pumping wells. For successful assessment of groundwater potential in such an area the estimation of the aquifer parameters is vital. The aquifer in the micro watershed in a granitic terrain is delineated through detailed hydrogeological investigations. The aquifer is found to be of the local type or of limited extent. Pumping tests have been carried out to estimate the aquifer parameters at 8 established locations. The interpretation of the data has been carried out at these places considering the limited extents of the aquifers and so aquifer parameters were estimated. Slug tests are often conducted in poor yielding boreholes where pump testing cannot be conducted.

The Study Area Description

Pallisa District within the Kyoga Basin is the area under investigation and is located in the eastern part of Uganda. It is approximately 1 585 km^2 in area and is bordered by Kumi District to the north, Budaka District to the east, Butaleja District to the south - east, Namutumba District to the south, Kaliro District to the west, to the north - west lies both Kamuli District and Soroti District. The chief town is Pallisa and its coordinates are 01^o 1’’N, 33^o 43’’E (Figure 1B).

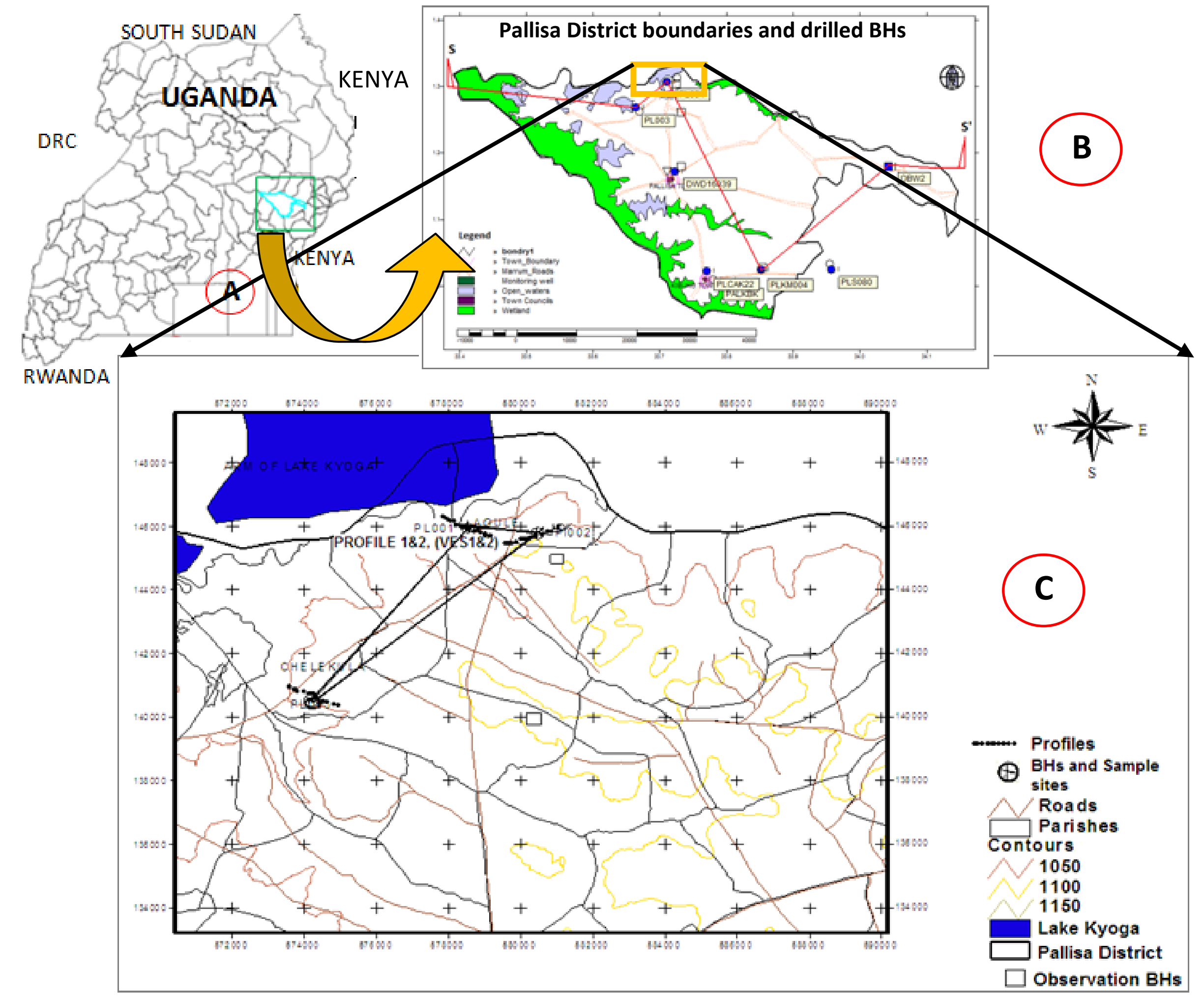

Figure 1: Location of the study area

Pallisa District is located between latitude 33^o 25’’E and 34^o 09’’E and Longitude 0^o 50’’N and 01^o 25’’N. There are small towns of Kabwangasi, Kamuge, Kibuku and Butebo within Pallisa district. The topography slopes gently from east to west with land surface elevations from 1 200 mamsl in the eastern part to near 1 000 mamsl in the south - western part (Figure 2). Most of the land is used for small scale agricultural farming while wetlands, woodland, bush land, grassland, deciduous plantations and urban areas represent about 30% of the land surface. The average temperatures range between 20 - 30 ^oC, with minor daily temperature variations. Mean annual minimum temperature is 18 ^oC and the mean annual maximum temperature is 32 ^oC. The weather conditions are characterised with bi - modal rainfall system controlled by the Inter - Tropical Convergence Zones (ITCZ) [5]. The mean annual precipitation is about 1 250 mm/year.

Local geology

The structural geological history is complex. Major structural features include the northwest and eastern areas and the step or en-echelon faulting associated with the western and eastern rift valleys. The crystalline rocks of Pallisa are generally covered by 'regolith', a layer of weathered material which varies from rock fragments near the interface with the bedrock, to well-weathered soil and sometimes hardened laterite at the ground surface [6, 7] and [8]. Sedimentary deposits of Paleozoic to early Tertiary are absent, except for minor fault - bounded outliers of the ecca shales (Karoo, Mesozoic). In mid to late Tertiary, up to 3 000 m of mainly lacustrine deposits (Elgon beds) accumulated in the eastern rift valley and along the river and lake valleys which are recent accumulation and depositions.

Hydrogeology

Groundwater is the most important source of potable water in Uganda, especially in the rural areas, and provides 80% or more of the water supply. Water in the study area is abstracted from both the fractured bedrocks and from the overlying weathered regolith (BH PL003; BH OBW2). The regolith aquifer is seen increasingly as a usable resource which aid agencies are seeking to develop on grounds of favourable yields and lower cost than the deeper groundwaters from the basement (BH PL004) [9, 10] (Figure 2).

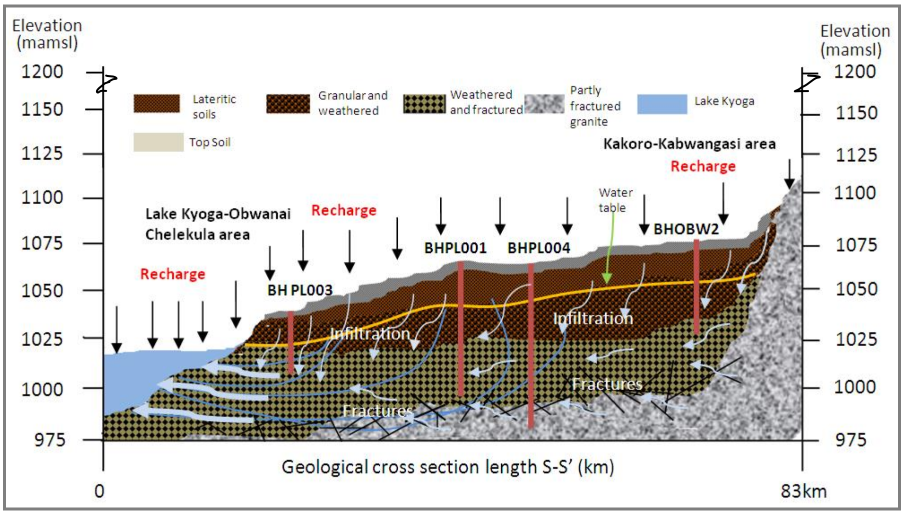

Figure 2: Schematic hydrostratigraphic units of the Kabwangasi - Kakoro - Lake Kyoga exaggerated cross-sectional conceptual geological model of groundwater flow in Pallisa District, eastern Uganda (Not to scale). Arrows show concentration of recharge

The regolith layer typically has an upper horizon of clayey sediment which is effective at filtering out some surface-derived pollutants (e.g. bacteria) and in restricting entry of air to the underlying aquifers [11]. This has some implications for the degree of aeration of the aquifers and of the resulting groundwater chemistry. The basement aquifer has poor permeability but is variably fractured. The development of fractures is crucial for the availability and yield of groundwater; hence the productivity of the aquifer is highest at the shallowest levels. According to [12] and [13], the high rainfall and temperature of tropical climates serve to increase the rate at which chemical weathering processes occur as a result of hydrolysis, oxidation and dissolution. The geopetal imprint of long-term deep weathering and erosional unloading was identified in the vertical heterogeneity of the fractured-bedrock and weathered-mantle aquifers; the horizontal heterogeneity is lithologically controlled. The two units form an integrated aquifer system in which the more transmissive (5-20 m^2/d) [13] and porous weathered mantle provides storage to underlying bedrock fractures ($T = 1\ m^2$/d). The thickness and extent of the more productive weathered-mantle aquifer are functions of contemporary geomorphic processes.

Methodology

The Vertical Electrical Sounding (VES) was done (Figure 1). A total of three (3) traverses were established, with traverses one and three trending North-West (N-W), and traverse three trending North-East (N-E) (Figure 1C). The Vertical Electrical Sounding (VES) stations were located based on the results of refraction survey. The VES technique was employed for the resistivity method. More than six VES stations were occupied with electrode separation (AB/2) varying from 1 to 65 m. The resistivity exploration technique employed for horizontal electrical resistivity profiling (HRP), involved the use of a geophysical resistivity meter (An ABEM terrameter SAS 300C). The seismic refraction data were plotted as time-distance graphs, while the vertical electrical sounding (VES) data were presented as depth sounding curves. The interpretation results of the seismic refraction time-distance graphs were used to construct geo-sections showing the subsurface layers that show geological relationship and weathering profile which depicts the various subsurface lithology units of Pallisa District. Also, the interpretation results of the VES curves were used to construct geo-electric sections showing the subsurface layers, their corresponding resistivities and thicknesses.

Theory of Aquifer Parameters Estimation

The solution to this problem is in the Cooper - Jacob method, where a well efficiency which is the specific capacity after 60 minutes of pumping, is divided by the theoretical possible specific capacity and calculated from the formula of Theis (equation 1):

$$s(r,t) = \frac{Q}{4\pi T}\int_{u}^{\infty}\frac{e^{-y}}{y}dy \qquad (1)$$

that reduces to

$$s(r,t) = \frac{Q}{4\pi T}\left[W(u) + \sum_{i=1}^{n} W(u_i)\right] \qquad (2)$$

and

$$u = \frac{Sr^2}{4Tt_0} \qquad (3)$$

Where T is transmissivity (m^2/d), S is storage coefficient (dimensionless), Q is pumping rate (m^3/d), $s(r,t)$ is drawdown (m) at a distance r (m) to the observation well and time t (d) after pumping began, n is the number of observation wells from the *ith* image well and $W(u)$ is the well function of u

Secondly, if the pumping rate is large and the observation well is near the pumping well, dewatering of the aquifer may be significant, and the assumption that the transmissivity of the aquifer being constant is not satisfied. The effect of dewatering of the aquifer can be eliminated with the following correction of the observed drawdown in equation 4.

$$s' = s - \left(\frac{s^2}{2b}\right) \qquad (4)$$

where b is the aquifer thickness, and s' is the drawdown that would have occurred if the aquifer had been confined. Hence, to determine the transmissivity and storage coefficient of an unconfined aquifer, a data plot consisting of s' versus t (or t/r^2) is matched with the Theis type curve of $W(u)$ versus $1/u$.

The slope of the straight line is proportional to the pumping rate and the inverse of transmissivity, hence using the Time - Drawdown method, the computer aided program Aquitest, calculates transmissivity and storativity in the following equation 5:

$$T = \frac{2.30Q}{4\pi[\Delta(h_2 - h_1)]} \qquad (5)$$

where, T = Transmissivity (m^2/d), Q = Discharge (m^3/hr) and $\Delta s = \Delta\,(h_2\text{-}h_1)$ (m) (Figure 27) is the change in drawdown over one logarithmic time cycle, and t_o is the time value where the straight line fit of the data intersects the time axis and the intercept of the line is proportional to the storage coefficient (S) and inverse of transmissivity (T), hence equation 6.

$$S = \frac{2.25Tt_0}{r^2} \qquad (6)$$

Pumping Test Data Analysis of Shallow and Deep wells around Pallisa town

Studies show that the demand for water in Agule has increased tremendously following an increase in population and cattle rearing. To meet the ever increasing demand for water, several groundwater investigations have been made in the study area, including the 1:250 000 scale hydrogeological maps (Figures 3, 4 & 5) which cover the study area. In 2002 the water table of the well field was found to be declining [14]. Hence, additional investigations were carried out from 2004 to 2006, during which eight test wells were drilled in search of a sustainable aquifer within 10 - 30 km radius of Pallisa.

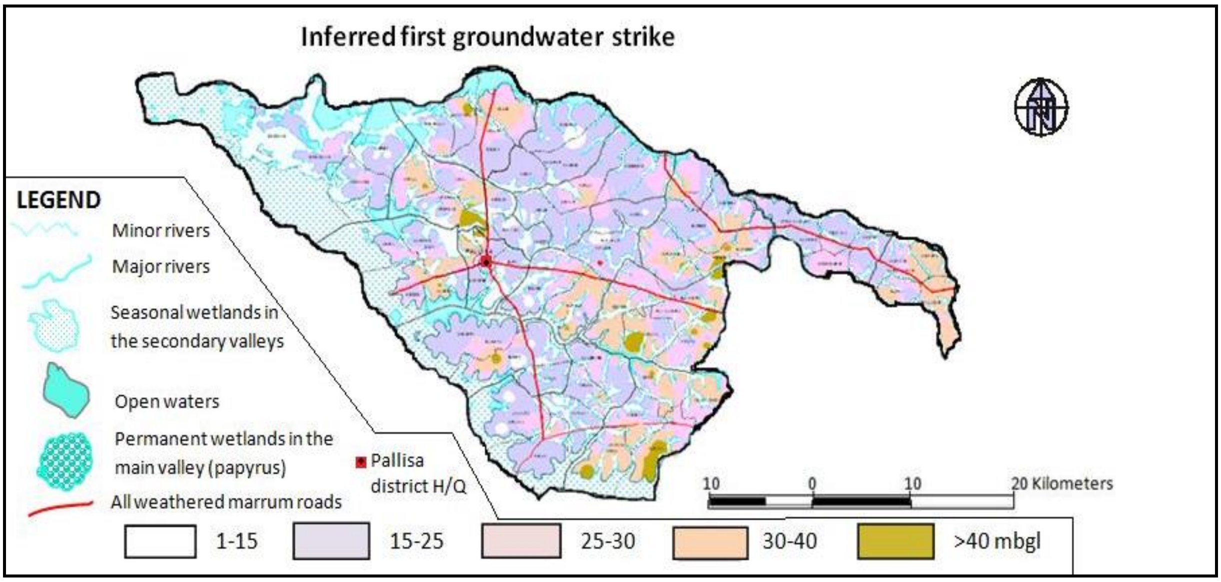

Figure 3: Inferred first groundwater strike in Pallisa District. Source: [15].

Water levels of the boreholes were monitored for at least four days prior to the test. It was found that all the wells exhibited more or less negligible change in depth of water level below ground level prior to pumping test. The discharge rates during the pumping test were kept a pre - determined rates and constant in some and others had variable pumping rates. Some characteristic curves were obtained with extension of pumping duration. Recovery was observed for a few minutes in some boreholes.

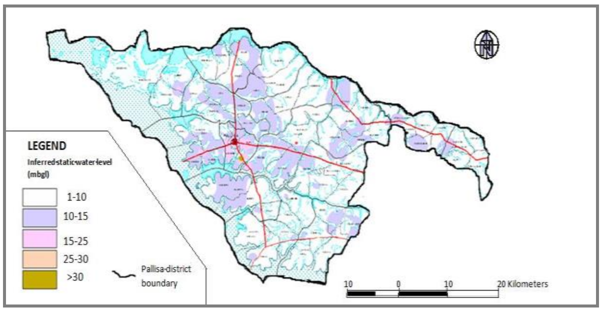

Figure 4: Inferred static groundwater level in Pallisa District (source: [15])

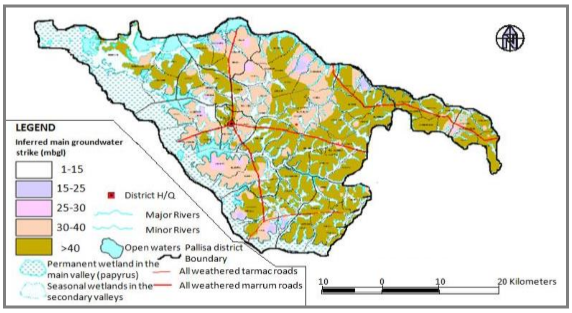

Figure 5: Inferred main groundwater strike in Pallisa District (source: [15])

Results and Discussions

Interpretation of Test Data

In an effort to characterise the granitic terrain where the aquifer is of local type and of limited extent, the effect of the nearby boundaries became prominent in the time drawdown data which meant a modification of the conventional expression for drawdown as indicated in equation 2 above.

Table 1: Time and step-drawdown results of the drilled boreholes

S/N	Test site	Discharge rate (m^3/d)	Duration of pumping (hrs)	Max. drawdown (m)
1	PL001	51.84, 95.04, and 138.24	2	45.0
2	PL003	69.12	4	25.1
3	PLS080	146.02	6	7.0
4	PLKM004	184.90	9	16
5	PLCAK22	233.28	1.33	1.9
6	DWD16039	79.5, 129.6, and 216.00	3	8.4
7	PALKBK	241.92	3	12.93
8	KBH1	43.20	1.33	

Seven test wells (PL001, PL002, PL003, PLS080, PLKM004, PLCAK22, and PALKBK) were drilled within Pallisa District (Table 1). The concentration of the test wells in the north - west and the southern part of Pallisa District indicates that more emphasis is given to this area, probably due to its proximity to Agule, Pallisa, Kibuku and Budaka towns, its low lying position within the Kyoga basin, and availability of previous hydrogeological information. Through geological logging, the depths, integrated EC, dissolved oxygen, pH, ORP and temperature measurements for PL002, PL003 and PLKM004, (Figures 8, 9, 29 respectively) were conducted in order to understand the variation in water quality with depth, and its correlation with lithological units (except PL001, DWD16039, PLS080 and PALKBK). Major and minor chemical constituents were also measured for all the test wells. The lower aquifer is assumed to be regional and at some places connected to the upper aquifer. Geophysical investigation also indicates the presence of penetrative faults, possibly connecting both aquifers. Because most of the test wells are open to both aquifers, we consider the system as single unconfined aquifer for analysing the pumping test data. As the drawdown measurements are made in the pumping well itself, only the transmissivity can be calculated from the time drawdown graph, and not the storage coefficient.

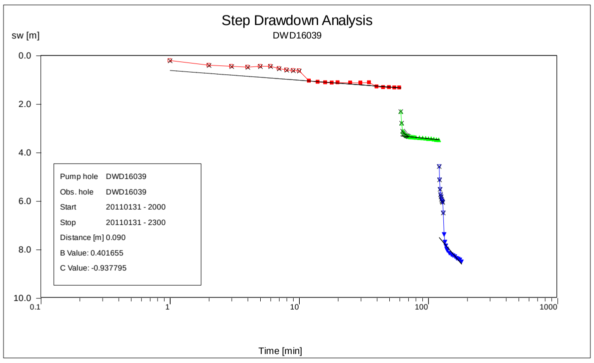

Figure 6: Step-drawdown test on well DWD16039.

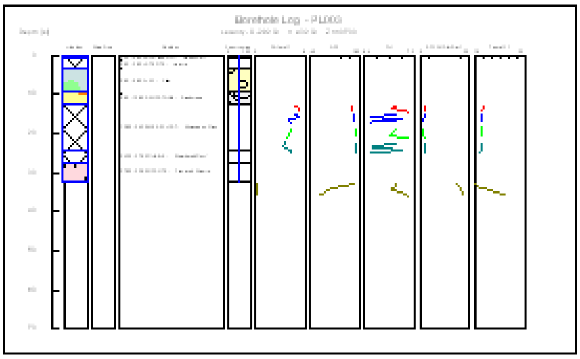

Figure 9: Borehole lithological log of test well PL003.

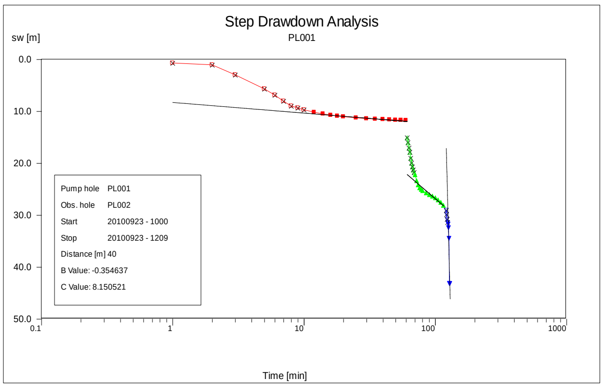

Figure 7: Step-drawdown of test well PL001.

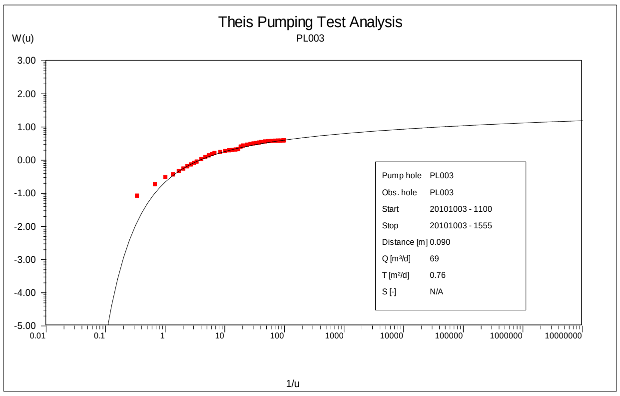

Figure 10: Theis graph for test borehole PL003.

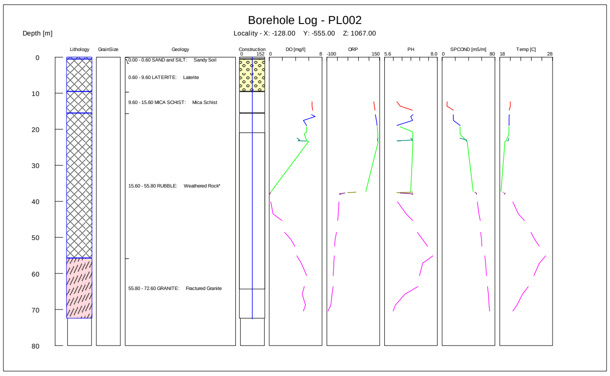

Figure 8: Borehole lithological log of observation well PL002.

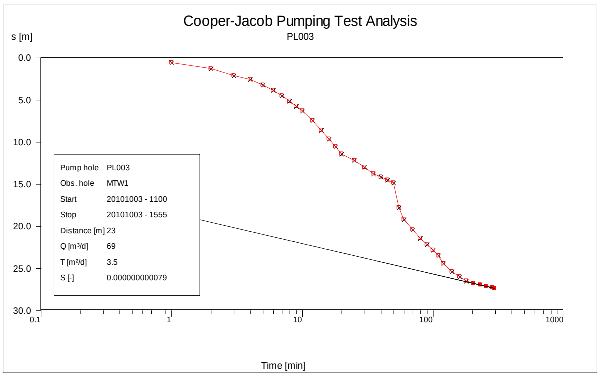

Figure 11: Time-drawdown graph for test borehole PL003.

Aquifer test analysis and characterisation using the FC - method to a single pumping well PLKM004

Pallisa District generally assumes a simplified two - layered aquifer system consisting of shallow unconsolidated and relatively homogeneous and porous regolith with a seemingly water-table aquifer that slowly supplies water downward to the underlying variable fractured crystalline bedrock. Interconnected fractures in the crystalline bedrock act as conduits for predominantly downward vertical and limited horizontal flow. In this research, detailed hydrogeologic studies in Pallisa District reveal a substantially different framework for groundwater flow. The shallow aquifer occurring within the laterite (within the saprolite) and the top of the bedrock is often separated from the underlying fractured bedrock aquifer by an aquitard (this can be observed from the lithologic logs, Figures 24 and

28). Hydraulic heads between the shallow aquifer and the deeper bedrock fractured aquifer can vary by 30 - 60 m vertically. Both of these aquifers are commonly encountered under confined aquifer conditions. Aquifer testing of the regolith - bedrock fracture system occurred over a period witnessed in the graphs (Figures 26 and 27) and produced rapid and relatively uniform drawdown in the fractured bedrock aquifers. This information combined with geophysical logging data indicates that horizontal flow is predominant in the bedrock fractures.

Diagnostic tools for characterisation of groundwater flow in fractures

The diagnostic tools have been used to characterise the groundwater flow from pumping in Pallisa as described by Van Tonder [16] that includes the straight line and derivative analyses. This was applied to a single borehole PLKM004. The following information was critical while dealing with log - log plot or semi - log:

(1). Two closed boundaries show a slope of 0.5; (2). There is a limited reservoir (four closed boundaries) when the slope is 1; (3). Fracture storage show a slope range of 0.5 - 1 for a linear flow and 0.25 - 1 for bilinear flow and well bore storage show a slope of 1 at early-time. While the semi-log plot provides information regarding the presence of boundaries:

(a).Two perpendicular closed boundaries quadruples the slope of the radial - acting flow; (b). One closed boundary doubles the slope of the radial acting flow straight line and (c). Only one straight line will be observed when all the boundaries are located equidistant to the pumping well, if not each boundary will increase the slope of the previous straight line reached.

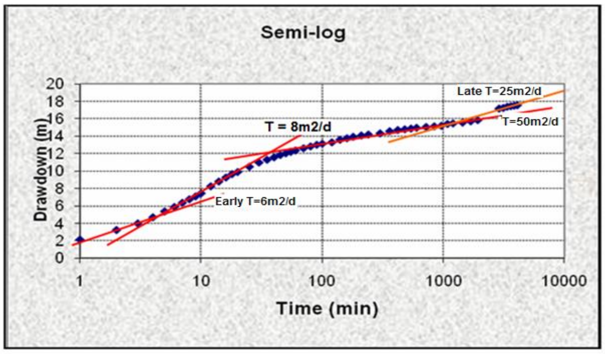

Figure 12: Analyses of an ambiguous drawdown time series where late - time response occurred after about 3500 minutes of pumping for borehole PLKM004

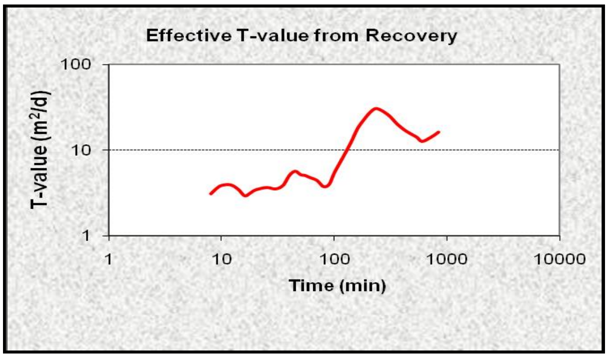

Figure 13: Log - log diagnostic plot of effective T - value from recovery data for borehole PLKM004.

[17] introduced the derivative plots that provided a simultaneous presentation on a log - log plot versus time and rate of drawdown change versus time. These derivatives curves have the advantage of being sensitive to small changes in the drawdown curves and are independent of the skin effects as described by [18] with the availability of advantages provided by [19] below:

(i) A closed no flow boundary shows a straight line with a slope of one (1) at late - time;
(ii) A single no - flow boundary shows at most a doubling of the derivative and two no-flow boundaries at - most a tripling of the derivative;
(iii) A double porosity aquifer shows a dip in the derivative slope after well bore storage;
(iv) Radial acting flow phase is plotted as a horizontal line;
(v) Borehole storage shows a slope of one (1) at early - time;
(vi) A recharge boundary shows a drastic decrease in the value of the derivative;
(vii) Positions of the fractures are usually seen by the decrease in the derivative at the fracture and an increase in the derivative after the fracture has been dewatered.

The interpretation therefore, was uncertain in crystalline fractured aquifers where transmissivity ranged between 6 and 50 m^2/d while matching various times of the drawdown curve (Figure 12). A similar transmissivity of 25 m^2/d was estimated by applying the Cooper - Jacob method to the late - time drawdown data and comparing Figure 12 with Figure 13. Better transmissivity estimates were obtained by interpreting early - time data after wellbore storage effects had dissipated. Identification of the early - time slope was ambiguous. Late - time drawdown was not observable until about 3 500 minutes of pumping had occurred (Figure 12).

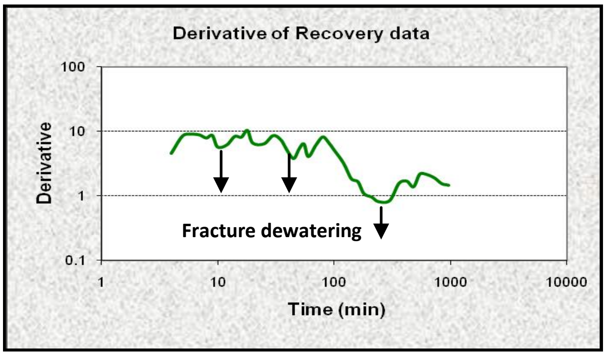

Figure 14: Log - log diagnostic plot of derivative of recovery data for borehole PLKM004.

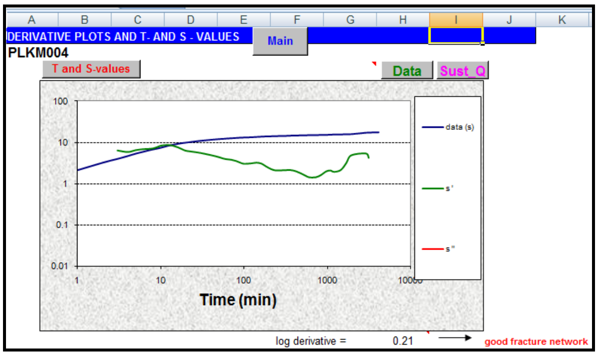

Figure 15: Flow Characteristic generated pumping test plot for well PLKM004 in a two-layered aquifer.

Figure 14 shows Iog - log diagnostic plot of the recovery data for borehole PLKM004. The derivative was calculated based on [20] and [21] equivalent time function for recovery data. The derivative shows a maintained alternation up to 90 minutes corresponding to varying transmissivities (Figure 13) and a steady decline derivative corresponding to a steady increase in transmissivity up to about 50 m^2/d for the next 210 minutes of recovery and then begins to increase. The derivative after 300 minutes may reflect either a stabilisation caused by radial flow conditions, or the increasing derivative expected at the beginning of the delayed - yield response. The test was however, not conducted for long enough a period to allow for correct interpretation. Time - drawdown plots were also constructed for wells completed in the shallow and deep fractured aquifers. Figure 15 is an example of the time - drawdown response of the deep aquifer during pumping for well PLKM004; located 25.5 km north - west of Pallisa town at 129.86 deg measured from the 2011 Map Link/ Tele Atlas of Google Earth.

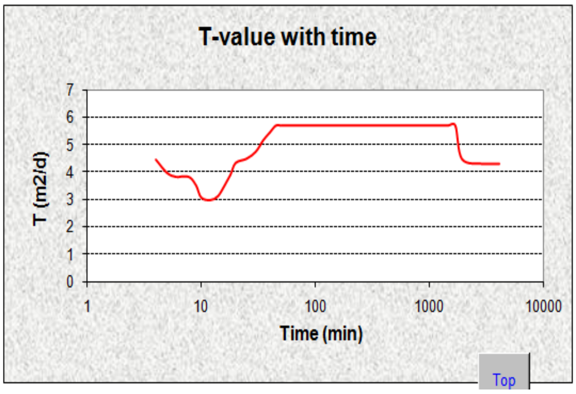

Figure 16: Transmissivity - Time plot for pumping well PLKM004.

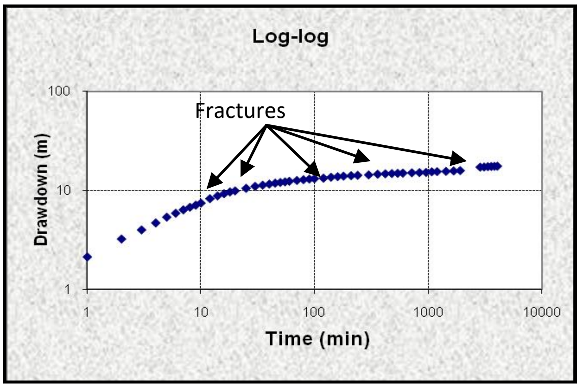

Figure 17: Time - drawdown log - log plot for well PLKM004. Half unit linear plot suggests a good transmissive fracture network.

Estimated transmissivity values from recovery data at the well indicate intersection of the likely fault zone in the deep aquifer that is between 3.0 and 5.8 m^2/d (Figure 16). This range signifies the importance of the deep aquifer system as a permeable water-producing and storage zone relative to the overlying saprolite aquifer or shallow bedrock.

In Figure 17, the early - time response to pumping indicates the time - drawdown plot has a half unit linear slope on log - log paper. It is also evident that a number of discrete fractures were dewatered.

This response may indicate a good transmissive fracture network [22] or a transmissive fracture set with significant well - bore storage effects [23].
After approximately two hours the plot follows a straight line with a slope of 0.25. The abrupt change is likely due to a lowered pumping rate corresponding to this time; however, the slope also likely represents horizontal parallel flow in a highly transmissive fracture similar to an extended well. Late time response corresponds to a period of pseudo - radial flow, which may indicate contributing flow from lower permeability fractures that intersect the major fault zone.

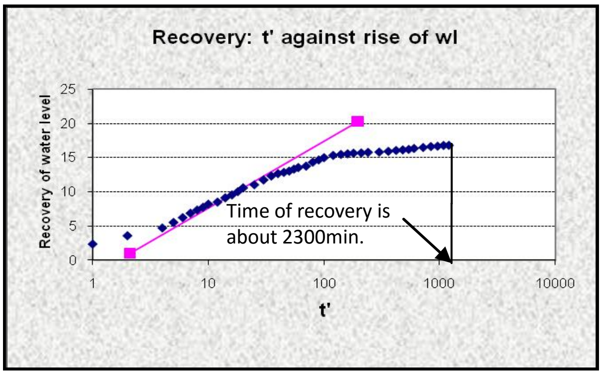

Figure 18: Recovery of water level against t' plot for well PLKM004.

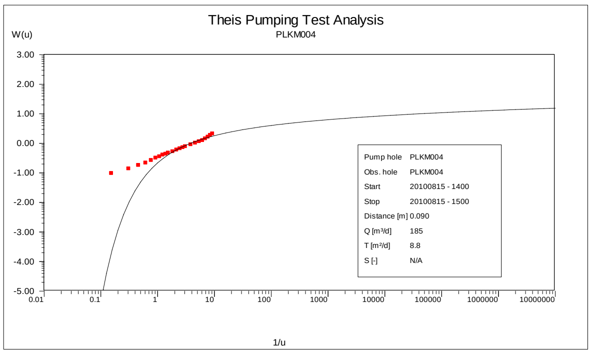

Figure 19: Theis pumping test analysis of test well PLKM004

A t' against water level rise plot of recovery data after pumping reflected a radial type flow system and suggests that the deep aquifer has a limited amount of water, and is ultimately being recharged from the overlying saprolite in localised areas referred to as breach zones, or by slow leakage through smaller, less permeable inter - connected fractures (Figure 18).
The Theis curve estimates transmissivity of borehole PLKM004 to be 8.8 m^2/d (Figure 19) with a 185 m^3/d of discharge in the first few hours of pumping. This was done to compare the transmissivities and discharges in interpretations for both the FC and WISH programs for the different days under the same conditions.

After seven hours of pumping at a rate of 1.69 l/s, the drawdown in PLS080 was about 7.10 m. Figure 20 shows the recorded drawdown data versus time plotted on a semi - log graph with a clear lithology (Figure 22). The Jacob method allows fitting a straight line through the last part of the data, yielding a change in drawdown Δs, value of 1.20 m over a log - cycle. The time - drawdown graph (Figure 20) produced by the WISH program, calculated transmissivity of the aquifer as 22 m^2/d with a storativity of $9.9 * 10^{-9}$ where the Theis differ in terms of the converted transmissivity of 9.6 m^2/d with no storage registered (Figure 21).

Test borehole PL001 is located at the upper most part of Pallisa District some 4.16 km west of bore well PL002 and about 2.87 km south west of PL003. PL001 is about 65 m deep and the static water level is at 8.9 m below the ground surface. The first water zone was struck between 22 - 27 m below the ground surface, indicating weathered granite aquifer and the second water strike was between 50 - 60 m indicating a fractured zone with appreciable quantities of groundwater.

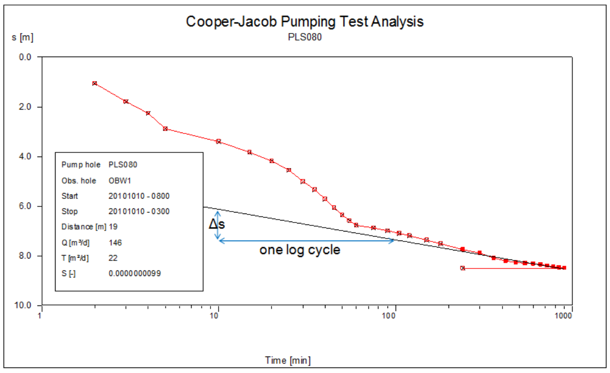

Figure 20: Time-drawdown graph for PLS080.

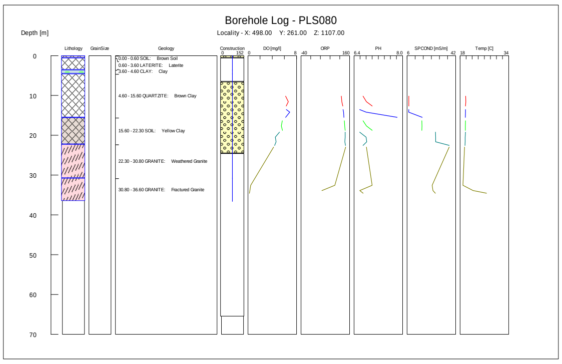

Figure 22: Borehole lithological log of test well PLS080

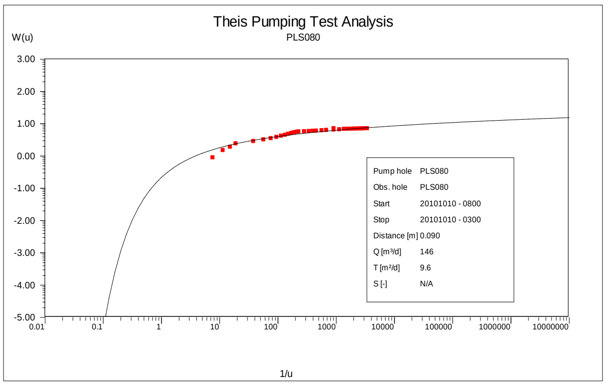

Figure 21: Theis pumping test analysis of test well PLS080.

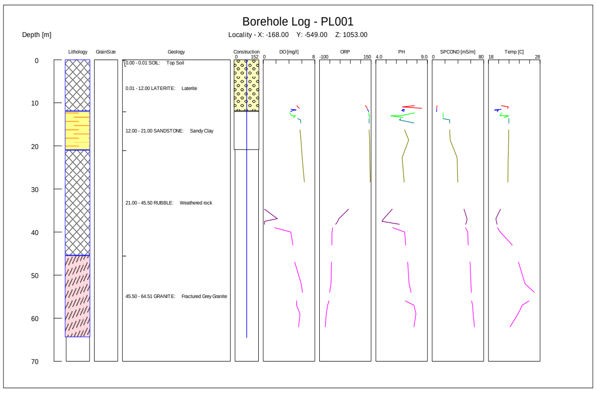

Figure 23: Borehole lithological log for test well PL001.

.The borehole penetrates through laterite, sandstone, weathered rock and fractured grey granite (Figure 23). The top 12.0 m of the section is dominated by one metre top soil with 11.0 m thick lateritic rock towards the top and two 10 m thick, slight to highly weathered and fractured, limestone layers. The lower part of the aquifer is separated by 24.50 m thick of weathered granite, underlain by 21.09 m thick and 24.50 m compact of fractured granite. The water bearing layers are the weathered and fractured granite in the lower half of the drilled section.

The time - drawdown and Theis graphs (Figures 24 and 25) of test borehole PLCAK22 give transmissivity values of 17 and 27 m^2/d using [24] methods respectively.

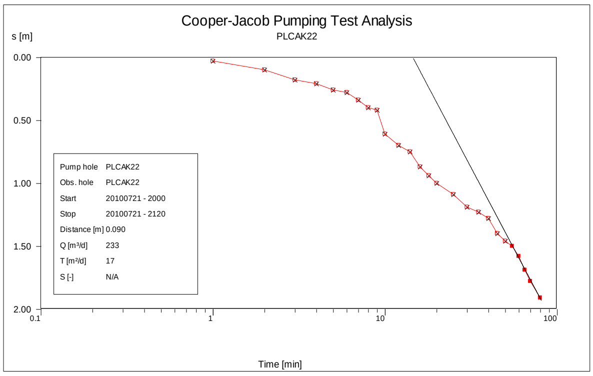

Figure 24: Time - drawdown curve for test well PLCAK22

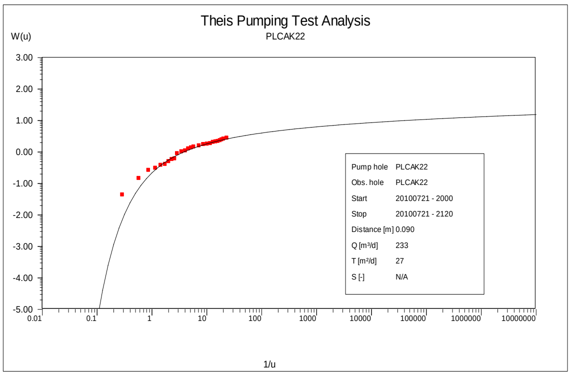

Figure 25: Theis pumping test analysis for test well PLCAK22.

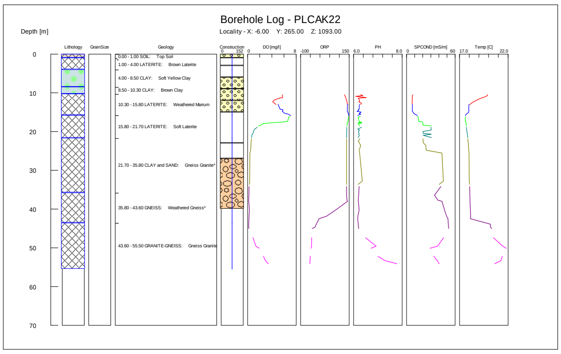

Figure 26: Borehole lithological log for test well PLCAK22.

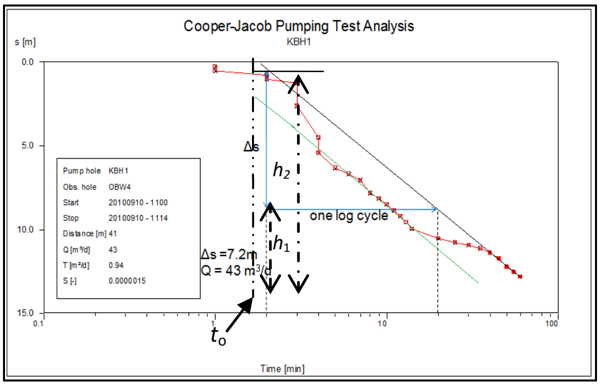

Figure 27: Time - drawdown curve for test well KBH1.

PLCAK22 is approximately 55.5 m deep with a static water level at 10.0 m below the ground surface. Figure 26 indicates that at the top part four geological units have been encountered: a top soil at the top, followed by soft yellow clay, brown clay, a weathered marrum and finally a soft marrum containing water. This is where the first strike of water was met. This is followed by 13.8 m of gneiss granite, 8.20 m of weathered gneiss and finally 11.90 m of fractured gneissic granite.
A pumping test was carried out for about one hour and 20 minutes at a rate of 0.50 l/s with a final drawdown of 12.93 m. Figure 27 shows the recorded drawdown versus time plotted on a semi - log graph. The irregularity of the drawdown record observed may probably be due to failure of a motor pump during which the water level in the well started to rise.
The trends of the data before and after this incident are nearly parallel. Hence, the second straight line is taken to derive the change in drawdown in one log cycle. Based on this straight line, Δs is 7.20 m with a transmissivity of 0.94 m^2/d and limited storativity of $1.5 * 10^{-6}$. Test well PLKM004 is located at the lower middle part of Pallisa District, almost half way between Tirinyi trading centre and surrounding village of Budaka. PLKM004 is approximately 90 m deep with a static water level at 11.0 m below the ground surface.
A pumping test was carried for nine hours at a rate of 2.14 l/s with a final drawdown of just 33.0 m. Figure 28 shows the recorded drawdown data versus time plotted on a semi - log graph. The Jacob method allows fitting a straight line through the last part of the data. Hence, from the graph (Figure 4-44) the transmissivity is calculated to be 1.2 m^2/d and storativity of $1.3 * 10^{-4}$ which is typical of fractured aquifers.

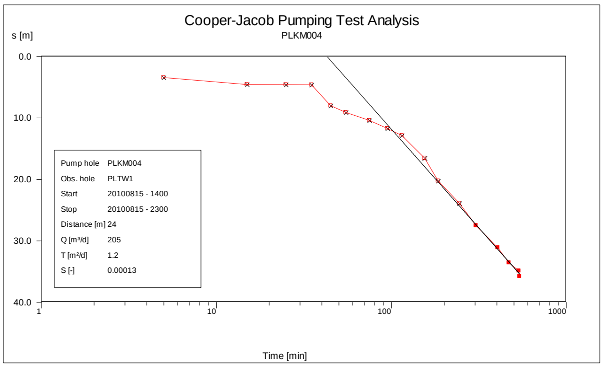

Figure 28: Time - drawdown curve for test well PLKM004.

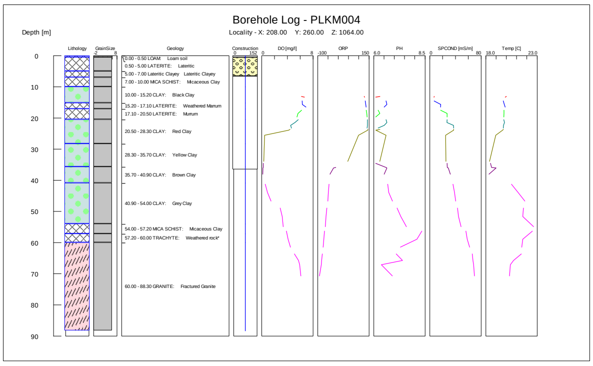

Figure 29: Borehole lithological log for test well PLKM004.

As can be noted from Figure 29, the top 20 m of the section includes 0.50 m of top soil, 4.50 m of laterite, three metres of micaceous clay, 4.20 m of black clay, 1.9 m of weathered marrum, and 3.4 m of marrum. The weathered rock is topped by 3.20 m thick micaceous clay. The lower 28.30 m thick section is made up of fractured granite. This layer is highly weathered and fractured and is identified as the water bearing layer.

Method of Analyses and Discussion

Due to the poorly defined aquifer boundaries and difficulties in determining the thickness of the major aquifers in the crystalline bedrock where the aquifers are structurally controlled, the computation of the hydraulic conductivity or coefficient of infiltration values (K) of the various aquifers presented some problems. The values of K were mainly obtained from pumping tests. In most cases, the thickness of promising aquifer zones, which invariably were fitted with screens, was used in the analysis. The K values were computed for the various rock types using the relation:

$$K = T/b$$

Where, T = transmissivity (m^2/d)
b = saturated thickness of aquifer (m)
For a reliable yield estimate, at least a 24 - hour pumping test is required. However in most instances, only three - hour pumping tests were carried out. Determining the long term yield of a well from data collected during a short period well acceptance test is an important practical problem in groundwater potential evaluation. Yields obtained during short term aquifer tests and yield tests performed by blowing the well with air are supported in a large part by de - watering the fractures. These are apparent yields and are usually considerably higher than the long-term sustained yield. Since the data available were only from the production well, the estimate of the long - term yield was usually based on an analysis of specific-capacity data. The specific capacity (yield per unit drawdown) that gives the water yielding capacity of the aquifer was determined by the following relation in equation 7:

$$S_c = Q/h \qquad (7)$$

where S_c = is specific capacity ($m^3/d/m$) or (m^2/d),
Q = pumping rate (m^3/d); h = drawdown (m)
The use and interpretation of the specific (production) capacity of the test wells deserve a cautious approach. Several studies have been conducted to simplify aquifer parameter estimation methods by developing empirical relationships between transmissivity, T and specific capacity, S_c [25]. In fractured rock aquifers, the relationship was modified by [26] and later [27]. [28] simplified the Thiem equation using theoretical values for the log-ratio term.
Combining a mean value for the log-ratio term with other constants, the relationship between T and S_c reduces to:

$$T = A_1 S_c \qquad (8)$$

where A_1 is the dimensionless constant ranging from 0.9 - 1.52 with a mean of 1.18 [28], T and S_c as above defined.

Well loss correction

The specific capacity, S_c can be determined from the field data in various ways. Any corresponding pumping rate and drawdown measurement provide the value of S_c. Obviously a constant rate aquifer test would not provide a unique value unless a steady state condition is reached. However, the change of S_c over time at a constant discharge rate is minor [29]. Step - drawdown tests typically include several steps of constant pumping rates that increase for subsequent steps.
This was applied to boreholes PL001,varying pumping rates increasing from 0.60, 1.10 and finally to 1.61 l/s, and DWD 16039 from 0.92, 1.50 and 2.50 l/s, Figures 22 and 23. Values of S_c decreases with increasing pumping rates and reflect well losses that increase with higher pumping rates. [29] expressed the relationship between steady - state drawdown in a well and discharge as:

$$s_w = BQ + CQ^2 \qquad (9)$$

where B is the aquifer loss coefficient (d/m^2) and C is the well loss coefficient (d^2/m^5).
The aquifer loss term includes all laminar loss in the aquifer, while the well loss term comprises all turbulent losses around and in the well. Figures 22 and 23 demonstrate these actions. [30] showed that correcting for the well loss significantly reduces the uncertainty in the prediction by improving the

correlation between T and Sc and by narrowing the prediction interval that encompasses the estimated values with 95% confidence.

Implications for Smaller scale Pumping Tests

The smaller data collection allowed some portrayal of the bedrock aquifer in Pallisa district. However, a typical pumping test would not be nearly as long nor would there be not as many observation boreholes. Some of the data collected highlights how a smaller scale test may have provided an erroneous aquifer characterisation. In many crystalline bedrock aquifers characterised by fracture flow and minimal primary porosity it is likely that pumping well will obtain water from relatively few fracture zones. Due to economic constraints, the observation wells for the pumping tests were typically few and the aquifer tests of limited duration. Time drawdown curves developed from these few hours tests suggest linear flow domain because the early time data.

Conclusions

In the granitic terrains, groundwater is found to occur in the shallow-weathered and fractured zones. The unconfined - confined aquifer in micro - weathered and fractured granite is limited in nature and the decline in water level due to pumpage is found to be strongly influenced by the boundaries. The aquifer parameters as well as the yields were found to be highly variable. Two points were noted:

i. There is no credible correlation between yield and depth of the drilled boreholes. It is however apparently clear that beyond 60 m in some areas, the yields decline markedly implying fractures within the granite constitutes the main source of groundwater flow to boreholes; and
ii. The transmissivity values for the granitic aquifers range between 0.78 and 32 m^2/d. The storativity varies from 0 - 1.3 * 10^{-4}. These imply low to intermediate transmissive capacity in a fairly heterogeneous hydrogeologic and anisotropic medium.
iii. Based on the foregoing observations and hydrogeological investigations, it may be inferred that the aquifer has a limited extent. The observations also indicate that the aquifer potential decreases as one approach borehole OBW2 meaning the aquifer is bound by the impermeable zone in the east to north - east of Pallisa town where rainfall in minimum.

The results indicate the advisability of performing a structural analysis along with the aquifer analysis to characterise the bedrock aquifer particularly in low crystalline bedrock where a single fracture zone may yield most of the water to the well. The results also indicate that while response at the pumping well may suggest linear single fracture flow, with availability of more data, later time found that the aquifer responds to what would seem a radial flow.

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