

Multi-Method Evaluation of Pumping Test Data to Characterize the Fractured Meta-Carbonate Aquifer at the Ntanisha Well-Field in Chongwe District, Zambia

Misheck Mwanza^{1*}, Joel Kabika²

^{1,2} *Department of Civil and Environmental Engineering, University of Zambia, Lusaka, Zambia*

**Corresponding Author Email: mishequ.jr@gmail.com*

ABSTRACT

Groundwater remains a vital resource for socio-economic development; however, increasing demand has intensified pressure on aquifers, heightening their vulnerability to depletion and contamination. In Zambia, limited hydrogeological data further increases the risk of over-abstraction and inefficient well-field operation. This study presents a multi-method evaluation of pumping test data to characterize the fractured metacarbonate aquifer at the Ntanisha well-field in Chongwe District using constant-rate, step-drawdown and recovery pumping tests conducted on four production boreholes supplying Chongwe Town. Time-drawdown data were analysed using conventional analytical methods and the Flow Characteristic (FC) method to estimate transmissivity, hydraulic conductivity, storage coefficient and specific capacity. Results indicate a heterogeneous fractured aquifer with transmissivity ranging from 5.63 to 43.95 m²/day, storage coefficients from 8.7×10^{-6} to 4.96×10^{-2} , and hydraulic conductivity from 0.0561 to 0.3957 m/day indicating confined to semi-confined behaviour. Boreholes intersecting well-developed fracture zones exhibited higher specific capacities (0.58–0.64 Ls⁻¹m⁻¹) and sustainable yields (80 m³/day to 292.9 m³/day). The analytical approaches show that reliance on constant-rate pumping test alone can overestimate safe abstraction, whereas integrating the FC method provides a more conservative and operationally robust basis for well-field management. The study highlights the value of multi-analytical pumping test interpretation for groundwater development and sustainable management of fractured metacarbonate aquifers across similar hydrogeological settings.

Keywords: FC Programme; AQTESOLV; Method Derivative Fitting; sustainable yield; Aquifer characterization

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1. INTRODUCTION

The development of groundwater resources as a reliable source of water supply for agriculture and domestic use has become very popular among developing cities and towns. With the increasing development of the groundwater resources and the growing impacts of human activities on the aquifers, problems such as declines of groundwater heads and deterioration of groundwater quality have been observed in many places in the last decades (Zhaou, 2001). It is, therefore of great importance to efficiently manage groundwater resources due to not only the above-mentioned reason, but also the fact that groundwater quality is at risk of contamination by inflow of polluted water. In fractured aquifer systems, inappropriate abstraction may lead to environmental degradation and, in severe cases, the decommissioning of affected boreholes. For that reason, it is of great importance to apply efficient and cost-effective methods in well-field management via groundwater sustainability.

This research sought to improve groundwater resources management by using groundwater data obtained through pumping tests to analyze and model the ground water parameters in order to characterize the aquifer. This was achieved by evaluating the use of multiple pumping test interpretation approaches to characterize the fractured meta-carbonate aquifer at the Ntanisha Well-field in Chongwe district, Zambia.

The Chongwe catchment drew public attention during the dry season of 2012, 2013 and 2014 due to the emergency water supply required in Chongwe town (Government Republic of Zambia, 2014). Over the years, Chongwe township has been expanding at a steady rate, which has resulted in the need to meet the increasing demand for water supply for various socio-economic needs for the growing population. With this development among many of the challenges faced by the township is the gap between water demand and the available sources of water. In recent years, recurrent water deficit has occurred due to the low water levels in the Chongwe River, influenced by climate change variability. According to the records of the Department of Water Resources Development, formerly Department of Water Affairs, reaching back to 1968 with merely a few gaps, Chongwe River – at the gauging station 5-025 near Chongwe town – had previously recorded extremely low or no flow in very few years, namely in 1995, 1998 and 2005 (Nick, 2015). Furthermore, the reservoir has been drying up more frequently and for longer periods in recent years.

In view of the water shortages experienced in Chongwe, exploration of groundwater resources in Chongwe area at Ntanisha Village in order to supplement the diminishing surface water sources was developed and equipped with seven production boreholes accompanied by one monitoring borehole, which was completed with the installation of a telemetric equipment for monitoring the effects of abstraction on the groundwater reserves as well as to detect any presence of contaminants in the aquifer. Water level measurements from observation wells are a principal source of information on hydrologic stresses acting on aquifers and their influence on groundwater recharge, storage and discharge (Taylor & Alley, 2001).

Despite the strategic importance of this groundwater source, the well-field was established without a comprehensive characterization of the aquifer's system. Key hydraulic properties such as storativity, transmissivity, hydraulic conductivity and aquifer boundaries, were not quantified at the time of development, leaving the system vulnerable to over-abstraction, inefficiency and long-term aquifer degradation. Initial site selection and design of the well-field was based on groundwater mapping and borehole logging derived from hydrogeological sampling. However, this approach lacked the integration of aquifer response modelling, meaning that critical aspects such as spatial heterogeneity, fracture influence and dynamic storage behaviour were not adequately assessed. Given the fractured rock nature of the aquifer, assumptions of homogeneity may not suffice, as fracture-dominated systems exhibit high variability in hydraulic behaviour, which affects borehole yield and long-term sustainability.

This study addresses the knowledge gap by applying pumping test analysis and aquifer parameter estimation methods to characterize the Ntanisha fractured aquifer system. The approach emphasizes empirical and field-based evaluation as a means to determine the capacity of the Ntanisha well-field to support sustained abstraction. By establishing key parameters such as transmissivity, hydraulic conductivity, storage coefficient and specific capacity, the research offers a foundation for estimating safe yield and identifying favorable boreholes for sustainable operation of the well-field. The findings are expected to improve current wellfield management practices and provide a benchmark for the development of future groundwater supply systems in similarly complex hydrogeological environments in Zambia. In doing so, the study contributes to the ZAWAFE 2026 thematic focus on Accelerating Integrated Water Security and Resilience by promoting evidence-based groundwater protection and sustainable management. Through improved aquifer characterization and scientifically informed abstraction planning, the research supports the long-term resilience of groundwater resources and aligns directly with the conference topical theme of Groundwater Protection and Management.

1.1 Theoretical Foundation of Pumping Test Interpretation

Aquifer tests remain the primary field-based method for evaluating hydraulic properties such as transmissivity and storativity, which are fundamental to aquifer characterization and groundwater management. The Cooper-Jacob time-drawdown method is widely used due to its simplicity and graphical interpretation. Late-time drawdown analysis generally provides more reliable estimates of aquifer properties after early-time disturbances have dissipated and the cone of depression has expanded to represent a larger portion of the aquifer as concluded by Toth (1966), Neuman (1972) and Lachassagne et al (1989) as the values obtained are considered to be more reliable and represent the true reflection of the aquifer behaviour after the cone of depression has reached a larger and more representative portion of the aquifer (Tumlinson et al., 2006). However, reliance on late-time drawdown must be approached with caution as Gomo (2023) notes late-time data do not necessarily satisfy infinite-acting radial flow (IARF) conditions in heterogeneous aquifers affected by boundaries or lithological variability. Diagnostic plots are therefore recommended to verify flow regimes before applying the Cooper-Jacob method, particularly in fractured aquifers such as the Ntanisha system where transmissivity and storage properties vary spatially.

Application of AQTESOLV in Pumping Test Analysis

Analytical modelling software such as AQTESOLV has significantly improved pumping test interpretation by enabling comparison of multiple analytical solutions, including the Theis (1935), Cooper-Jacob (1946), Nueman (1972) and Moench (1984) models. Its automated curve-fitting, model selection and simulation of wellbore storage, skin effects and partial penetration make it particularly suitable for heterogeneous aquifers. Mbedzi et al. (2021) in Limpopo, South Africa, El-Fergany et al. (2021) in Lybia, and Ali et al. (2022) in Iraq, demonstrated its reliability in fractured and heterogeneous aquifer systems through improved model selection and close agreement with manually derived hydraulic parameters. In this study, AQTESOLV was used to validate manually calculated parameters and assess model fit under fractured aquifer conditions.

Application of the Flow Characteristic (FC) Method

Utilizing vital information from pumping tests, the FC method makes use of drawdown derivatives and subjective information on no-flow boundaries to estimate a sustainable borehole yield that should not cause the water level to drop below the main strike (fracture) during long-term operation (Gomo M. , 2024). The FC Methods strength lies in its simplicity of use, its ability to protect the main water strike/fracture and its lower susceptibility to the influence of aquifer heterogeneities because it does not require the input of aquifer storativity and transmissivity (Gomo M. , 2024).

The FC method is based on the rationale of borehole sustainable yield, defined as the pumping rate that does not cause the water level to fall below the main fracture/water strike during the operational period, coined by Van Tonder et al. (2001). This has the same definition as safe yield. To estimate the sustainable yield, the FC Method uses the relationship between the pumping test constant discharge rate (Q_p), and the measured and extrapolated drawdown from the production well Van Tonder et al., 2001) as shown in equation 1 below.

$$Q_s = Q_p \frac{s_a(t = t_{long})}{s_p(t = t_{long})} \quad (1)$$

where t_{long} describes the maximum operation time in which the drawdown s shall not exceed a maximum drawdown (s_a) during the operation period of the borehole; $s_p(t=t_{long})$ – drawdown measured during the pumping test that is extrapolated over t_{long} ; Q_s – long-term sustainable borehole yield that should not lower the water level below the main fracture.

The drawdown measured during a pumping test is the sum of the drawdown due to the production well (s_{well}) and the boundaries ($s_{boundary}$) as shown in equation 2.

$$s(t = t_{log}) = s_{well} + s_{boundary} \quad (2)$$

The FC Method was chosen for this research not only for its simplicity in applicability, but also accounting for the complex data collected during the pumping tests real field conditions. It is ideal for evaluating parameters such as sustainable yields of complex heterogeneous aquifers without the use of long-term monitoring data. This method adapts well to systems with non-linear drawdown behaviour and varying transmissivity, which are common features of heterogeneous aquifers (Kruseman & de Ridder, 1991), and aligns with the study objective of defining safe abstraction limits under structurally complex conditions.

Method of Derivative Fitting (MDF)

The introduction of the Method of Derivative Fitting (MDF) for the analysis of constant rate tests was as a result of its application in hydraulic tests used in developing water supply schemes for rural communities in South Africa where aquifer geometry is uncertain (Van Tonder et al., 2001).

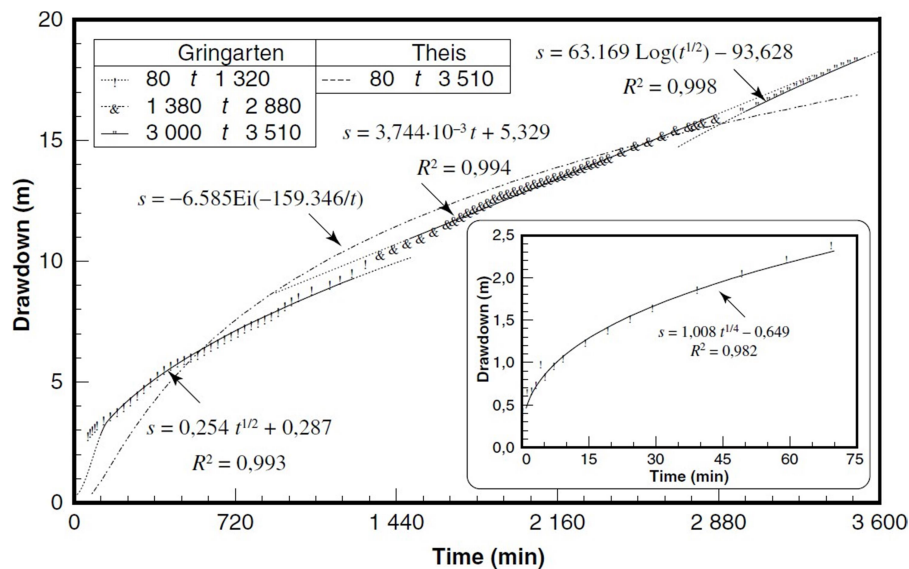


Figure 1: The drawdown observation by Botha et al., 1996 fitted to the type curve of Gringarten and Ramey for an aquifer intersected by a horizontal fracture and Theis curve for a horizontal porous aquifer

The MDF is particularly effective in identifying complex flow regimes and boundary effects in fractured and heterogeneous aquifer systems. Unlike traditional approaches that solely rely on drawdown-time data, MDF focuses on the logarithmic derivative of drawdown with respect to time, which provides enhanced sensitivity to changes in aquifer behaviour. The advantage of this approach is that small variations in the pressure can be more easily recognized in a graph of the time derivative of the pressure than in a graph of the pressure (Van Tonder et al., 2021)

One way in which to apply the MDF is to simply fit the derivative of a conventional type curve directly to the first divided differences of the observed drawdown, s , defined by equation 3 below.

$$\frac{\Delta S_i}{\Delta t_i} = \frac{(t_{i+1}) - s(t_i)}{t_{i+1} - t_i} \quad (3)$$

This, however, means that one must select a suitable type curve.

Radial flow can be characterized by the Theis equation as follows in equation 4,

$$s(r, t) = \frac{Q}{4\pi T} \int_u^\infty \frac{\exp(-x)}{x} dx = \frac{Q}{4\pi T} W(u)$$

$$u = \frac{Sr^2}{4Tt} \quad (4)$$

Where; Q is the discharge rate, T is the transmissivity and S is the storativity of the aquifer. The Derivative of this equation with respect to the logarithm of time, henceforth referred to as the log derivative, will there approach a straight line parallel to the time axis on a log-log graph of $s'(r, t)$ as $t \rightarrow \infty$, as illustrated in the figure 2 below.

$$s(r, t) = \frac{ds}{d\ln(t)} = \frac{Q}{4\pi T} \exp\left[\frac{Sr^2}{4Tt}\right] \quad (5)$$

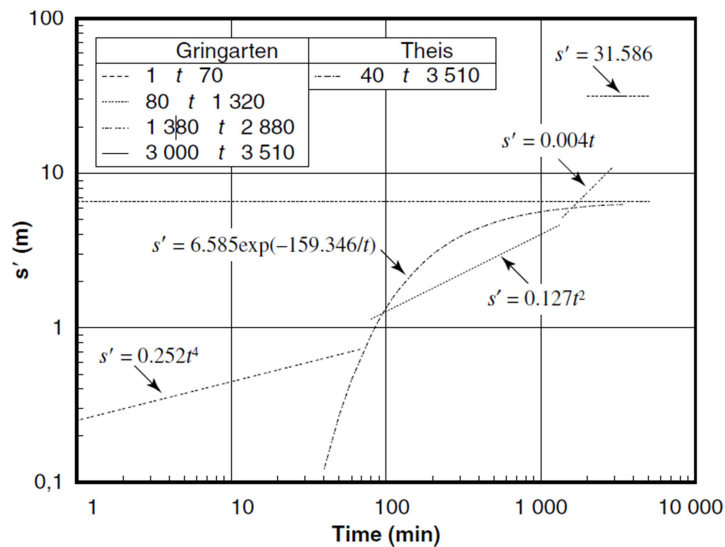


Figure 2: The log derivatives of the Gringarten and Theis fits to the water levels of borehole A05

This method allows for the detection of distinct flow regimes, such as early-time wellbore storage effect; mid-time radial flow behaviour (Theis-type response); Late-time boundary effects, e.g. Recharge or barrier boundaries.

MDF plays a crucial role in modern aquifer test interpretation frameworks, particularly within the FCM. By fitting both the drawdown and its derivative simultaneously, the MDF enhances model robustness and reduces non-uniqueness in parameter estimation.

Studies by Renard et al. (2009) and Horne (2007) have demonstrated that derivative-based methods significantly improve the interpretation of transient responses in complex aquifer systems, including dual-porosity and leaky aquifers. Renard et al. (2009) emphasized that diagnostic plots provide a unified framework for evaluating aquifer behaviour, as they simplify the identification of conceptual models even in variable-rate or noisy data conditions. The logarithmic derivative enhances the visibility of subtle flow regime changes, including infinite acting radial flow (IARF), leaky boundaries, delayed yield, or skin effects, especially in cases where traditional drawdown curves alone are ambiguous.

Furthermore, Renard et al. (2009) highlight that diagnostic plots, by analyzing both drawdown and its derivative in log-log scale, enable hydrogeologists to distinguish between various conceptual models by comparing the empirical curves to a catalogue of theoretical responses. This helps avoid misinterpretation, especially in cases involving early-time wellbore storage or late-time boundary effects. However, the method is sensitive to measurement noise and time shift errors, and therefore requires pre-processing and smoothing techniques to enhance signal clarity.

Heterogeneous Aquifers

The particular setting of the Ntanisha wellfield falls within a metacarbonate formation primarily composed of dolomite and limestone, known to host karst and fissured aquifers. Karst aquifers exhibit unique flow characteristic due to the presence of solution enlarged fractures, crevices, cavities and discontinuities, often resulting in highly productive zones interspersed with low yielding region (Ford & Williams, 2007). Aquifers of such nature are typically complex, consisting of rapid and turbulent flow pathways. This makes them vulnerable to both abstraction and contamination.

In these environments, uniform analytical assumptions may oversimplify aquifer behaviour and lead to overestimation of sustainable yields. Accurate characterisation therefore requires integration of conventional analytical methods with diagnostic and sustainability-focused approaches, as adopted in this study.

2. MATERIALS AND METHODS

2.1 Borehole network and pumping test design

The Ntanisha wellfield comprises seven production boreholes and one dedicated monitoring borehole developed within a fractured metacarbonate aquifer. For this study, four production boreholes (BH1, BH2, BH3 and BH4) were selected for detailed hydraulic analysis based on data availability and operational relevance. The boreholes have depths ranging from approximately 100 to 113 m and were completed with screened intervals intersecting fractured limestone and dolomite units.

These tests were carried out in accordance with hydro-geological field procedures for fractured rock aquifers and were designed to estimate key parameters such as transmissivity, hydraulic conductivity, specific capacity, and storage coefficient (Kruseman & de Ridder, 1991). The test sequence included: Step-drawdown tests, constant rate (continuous) pumping tests, and recovery tests. Time–drawdown and time–recovery datasets formed the basis for subsequent analytical modelling.

2.2 Step-Drawdown Test

The step was conducted in the Ntanisha well field on each borehole in order to determine the optimal constant discharge rate for the subsequent continuous test, while also identifying the main water strike zone and monitoring well behaviour under increasing stress and turbulence (Driscoll, 1986). The following table. 1, illustrates the summary of the step drawdown tests.

Table 1: Summary of Step-drawdown Pumping Test Record

Step drawdown Pumping Test Record Borehole 1				
Steps	Step 1	Step 2	Step 3	Step 4
Pumping rate Q l/m	150	174	198	258
Duration (min)	120	120	120	120
Static water level (mbtc)	1.65			
Step drawdown Pumping Test Record Borehole 2				
Steps	Step 1	Step 2	Step 3	Step 4
Pumping rate Q l/m	450	540	600	720
Duration (min)	120	120	120	120
Static water level (mbtc)	2.63			
Step drawdown Pumping Test Record Borehole 3				
Steps	Step 1	Step 2	Step 3	Step 4
Pumping rate Q l/m	450	600	750	900
Duration (min)	120	120	120	120
Static water level (mbtc)	1.01			
Step drawdown Pumping Test Record Borehole 4				
Steps	Step 1	Step 2	Step 3	Step 4
Pumping rate Q l/m	408	498	600	720
Duration (min)	120	120	120	120
Static Water Level (mbtc)	2.63			

2.3 Constant-Rate (Continuous) Pumping Test

The constant rate pumping tests were the primary method use to generate time-drawdown data, which was later analysed using three different approaches, which included the manual Cooper-Jacob method, and analytical models AQTESOLV and the FC Programme (Van Tonder et al., 2001). Table 2 shows the summary of the continuous discharge pumping test.

Table 2: Continuous discharge pumping test for borehole BH1 Summary

Constant Rate Discharge	Values
Borehole BH1	
Borehole depth (mbtc)	100
SWL (mbtc)	2.08
Drawdown water level (mbtc)	48.64
Pumping rate Q (L/s)	3.6
Borehole BH2	
Borehole depth (mbtc)	113
SWL (mbtc)	1.93
Drawdown water level (mbtc)	24.21
Pumping rate Q (L/s)	7.5
Borehole BH3	
Borehole depth (mbtc)	115
SWL (mbtc)	2.31
Drawdown Water Level (mbtc)	65.05
Pumping rate Q (L/s)	11.9
Borehole BH4	
Borehole depth (mbtc)	120
Drawdown water level (mbtc)	66.11
SWL (mbtc)	2.91
Pumping rate Q (L/s)	10.9

2.3 Recovery Test

Recovery data were used in AQTESOLV analysis to cross-check transmissivity and interpret aquifer behaviour beyond the influence of early-time wellbore effect (Theis, 1935). The recovery curves were incorporated into the software workflow to improve parameter confidence. Table 3 below shows the summary of the recovery test.

Table 3: Recovery test summary

	Borehole BH1		Borehole BH2		Borehole BH3		Borehole BH4	
Time	Water Level (m)	Recovery	Water Level (m)	Recovery	Water Level (m)	Recovery	Water Level (m)	Recovery
0	49.14	47.06	24.21	22.28	65.05	62.74	66.11	63.2
1	46.31	44.23	14.02	12.09	35.88	33.57	36.16	33.25
2	43.39	41.31	11.33	9.4	24.1	21.79	35.32	32.41
3	40.32	38.24	9.37	7.44	19.32	17.01	35.02	32.11
4	37.21	35.13	7.77	5.84	15.18	12.87	35.01	32.1
5	33.95	31.87	6.75	4.82	12.27	9.96	33.13	30.22
6	30.72	28.64	5.76	3.83	10.59	8.28	26.67	23.76
8	24.76	22.68	4.75	2.82	8.88	6.57	14.56	11.65
10	18.95	16.87	4.18	2.25	8.47	6.16	10.11	7.2
12	14.25	12.17	3.84	1.91	7.97	5.66	8.22	5.31
14	10.19	8.11	3.61	1.68	6.54	4.23	6.62	3.71
18	5.75	3.67	3.29	1.36	5.52	3.21	5.82	2.91
24	4.06	1.98	3.13	1.2	4.99	2.68	5.08	2.17
30	3.66	1.58	3.01	1.08	4.73	2.42	4.76	1.85
40	3.49	1.41	2.9	0.97	4.46	2.15	4.49	1.58
50	3.37	1.29	2.84	0.91	4.27	1.96	4.34	1.43
60	3.26	1.18	2.79	0.86	4.22	1.91	4.22	1.31
80	3.2	1.12	2.7	0.77	4.1	1.79	4.07	1.16
100	3.16	1.08	2.68	0.75	3.98	1.67	4.02	1.11
120	3.13	1.05	2.64	0.71	3.79	1.48	3.98	1.07
150	3.07	0.99	2.59	0.66	3.49	1.18	3.86	0.95
180	NA	NA	NA	NA	3.28	0.97	NA	NA
240	NA	NA	NA	NA	3.08	0.77	NA	NA
300	NA	NA	NA	NA	3.01	0.7	NA	NA
360	NA	NA	NA	NA	2.97	0.66	NA	NA
420	NA	NA	NA	NA	2.95	0.64	NA	NA

Note: NA (Data not available)

2.4 Data Analysis and Synthesis

Time-drawdown and recovery data were analysed using three complementary analytical approaches: The Cooper–Jacob approximation, AQTESOLV analytical modelling software and the Flow Characteristic (FC) method. The multi-method framework was adopted to accommodate the heterogeneous and anisotropic nature of the fractured aquifer system.

2.4.1 Analysis of Pumping Test Data via Analytical Modelling

The interpretation of pumping test data was performed using analytical modelling tool AQTESOLV and Flow Characteristics (FC) Programme.

Both tools provided complementary insights and were used to validate parameters across boreholes.

2.4.2 Method Derivative Fitting Cooper-Jacob

In addition to the software-based analysis, aquifer parameters were also estimated manually using the Method Derivative Fitting Cooper-Jacob straight line method. Drawdown measurements were plotted against the logarithm of time (log). The portion of the drawdown curve that formed a straight line was identified as the late-time linear segment.

Transmissivity (T) was calculated using the slope (ds) of the straight-line segment based on equation 6 shown below;

$$T = \frac{2.3Q}{4\pi\Delta S} \quad (6)$$

Storage coefficient (S) was estimated using the formula below of equation 7:

$$S = \frac{2.25 T t_0}{r^2} \quad (7)$$

Where, t_0 is the x-intercept time in days, where the extrapolated straight line intersects the time axis, and r is the radius of the pumped well.

With the graph preparation, time data was converted to logarithmic values e.g $\log_{10}(t) = 1 \text{ min}, 10 \text{ min}, 100 \text{ min}, 1000 \text{ min}$ and corresponding drawdown values were plotted to identify the linear trend. Show below is the graphs developed for B1, B2, B3 and B4. This method was particularly useful in validating transmissivity values and diagnosing well performance in the absence of observation well drawdown data. Table 4 below shows the drawdown against log-time data utilized in the analytical models, while the corresponding tables results obtained through the manual calculations.

2.5 AQTESOLV Analytical Modelling

AQTESOLV was used to fit analytical solution to drawdown and recovery data, a widely recognized software for interpreting pumping and slug test data. AQTESOLV is designed to estimate key hydrogeological parameters such as hydraulic conductivity, transmissivity and storativity using various analytical solutions. The program supports the importation of structured text files, allowing seamless integration of time-drawdown and recovery data collected during aquifer tests.

The software offers a broad suite of analytical models, including the Theis (1935) confined aquifer solution, the Cooper-Jacob approximation, and the Hantush-Jacob solution for leaky aquifers, among others. While AQTESOLV is a powerful tool, it provides minimal automated guidance on the selection of the most appropriate solution for a given hydrogeologic setting. As such, the user's expertise and understanding of aquifer behaviour are critical to ensure appropriate model selection and parameter fitting. To assist users, the software includes references to foundational literature on each method.

Although AQTESOLV features automated type-curve matching capabilities, manual fitting is strongly recommended to achieve a more reliable calibration between theoretical and observed drawdown data. In this study, data sets from the four boreholes (BH1 to BH4) subjected to constant-rate pumping tests at the Ntanisha well field were analysed using the Cooper-Jacob method. Essential input parameters such as well radius and saturated thickness (b) were specified for each test. The resulting time-residual drawdown plots for each borehole (BH1 to BH4) is presented on table 5 below. These plots illustrate the goodness of fit between the Cooper-Jacob solution and observed drawdown data, and form the basis for estimating transmissivity and storativity values for each borehole.

2.6 Flow Characteristic (FC) Method

The FC Method via the FC Programme based on the flow characteristic method developed by Van Tonder et al. (2001) was applied to estimate sustainable yield. It utilizes both basic and advanced solutions to model drawdown trends and extrapolate future behaviour under long-term pumping conditions. This method is particularly effective for fractured aquifer containing variations in parameters such as transmissivity and storativity (Gomo M. , 2024). The tool provided estimates for transmissivity, hydraulic conductivity, storage coefficient, and also helped identify boundary effects and flow regime transitions. Highlighted on table 6 below is the summary of the hydraulic parameter and sustainable yields of the boreholes at the Ntanisha wellfield.

3. RESULTS AND DISCUSSION

The aquifer underlying the study area was evaluated through constant rate pumping tests that were performed on borehole BH1, BH2. BH3 and BH4. Via the data from the pumping tests, different analytical models were utilized in order to understand the aquifer system of the study area. The approaches involve use of the Flow Characteristic (FC) Method via the FC Programme developed by van Tonder, et al., (2001) which operates in Excel, and the analytical software by HydroSolve, AQTESOLV and the MDF using the Cooper-Jacob method was done to assist in data validation. Key parameters considered in the characterization include transmissivity (T), hydraulic conductivity (K), sustainable yield (Q_{sus}), Specific storage (S_s) and storage coefficient (S) to name but a few. While, the use of different analytical approaches was applied to estimate these parameters, the focus of this discussion is aquifers response to the constant pumping and subsequently, the hydraulic properties inferred from the resulting values. The results generated through the applications are presented as shown in table 4.

3.1 Multi-method Analysis Summary

All tables must be numbered chronologically using Arabic numerals. Place headings directly above tables, center-aligned, with a clear single line space isolating the title text from the data matrix body.

Table 4: Results Summary obtained through the FC Programme, AQTESOLV and MDF

ID	Parameters	FC Method	AQTESOLV	Manual Calculations
BH1	Well Depth [m]	97		
	Water strikes [m]	16, 38		
	Borehole Pumping Yield Q (L/min)	216		
	SWL (mbtc)	2.08		
	Available drawdown (m)	35.92		
	Maximum drawdown S_{max} (m)	47.06		
	Sustainable Q (m ³ /day)	80.3		
	Transmissivity (m ² /day)	5.7	5.639	5.32
	Hydraulic coefficient K (m/day)	0.06	0.0594	0.0561
	Specific Storage Ss (1/m)	0.000769	0.00052	0.0012
	Storage coefficient	0.073	0.04962	0.12
	Specific Capacity SC (L/s/m)			0.33
BH2	Well depth [m]	113		
	Water strikes [m]	30; 41; 58		
	Borehole Pumping Yield Q (L/min)	450		
	SWL (mbtc)	1.93		
	Available drawdown (m)	29.5		
	Maximum drawdown S_{max} (m)	22.28		
	Sustainable Q (m ³ /day)	292.9		
	Transmissivity (m ² /day)	34.7	43.95	37.17
	Hydraulic coefficient K (m/day)	0.31	0.3957	0.335
	Specific Storage Ss (1/m)	0.000023	0.00000095	0.000016
	Storage coefficient	0.0026	0.0001	0.0018
	Specific Capacity SC (L/s/m)			0.64
BH3	Well depth [m]	115		
	Water strikes [m]	26; 36; 79		
	Borehole Pumping Yield Q (L/min)	714		
	SWL (mbtc)	2.31		
	Available drawdown (m)	23.7		
	Maximum drawdown S_{max} (m)	62.74		
	Sustainable Q (m ³ /day)	120.1		
	Transmissivity (m ² /day)	14.5	15.51	14.62
	Hydraulic coefficient K (m/day)	0.128	0.1376	0.13
	Specific Storage Ss (1/m)	0.0006	0.0002947	0.000079
	Storage coefficient	0.068	0.033	0.009
	Specific Capacity SC (L/s/m)			0.58
BH4	Well depth [m]	120		
	Water strikes [m]	33; 73		
	Borehole Pumping Yield Q (L/min)	654		
	SWL (mbtc)	2.91		
	Available drawdown (m)	30.1		
	Maximum drawdown S_{max} (m)	63.2		
	Sustainable Q (m ³ /day)	158.1		
	Transmissivity (m ² /day)	18.3	23.89	20.16
	Hydraulic coefficient K (m/day)	0.155	0.204	0.17
	Specific Storage Ss (1/m)	0.0000124	0.0000000743	0.0000018

Storage coefficient	0.00146	0.0000087	0.00022
Specific Capacity SC (L/s/m)			0.29

Transmissivity (T) across the borehole varies significantly, with value ranging from 5.3 for the lowest value and 43.9 m²/day for the highest value. Borehole BH2 and BH4 exhibit the highest values on transmissivity, indicating more permeable zones capable of transmitting substantial amounts of groundwater. BH1, with the lowest pumping yield at 216 L/min, shows relatively low transmissivity, suggesting either less permeable formations or partial penetration of the borehole into the aquifer zone.

The spatial variability in transmissivity may also indicate heterogeneous aquifer conditions, potentially influenced by differences in lithology, degree of weathering and varying fracture connectivity. The close agreement between transmissivity values obtained from the three analytical approaches confirms the reliability of the pumping test interpretation and supports the validity of the estimated hydraulic parameters.

The hydraulic conductivity values (K), which can be explained as the ability with which groundwater can move through porous zone and/or fractures, follow a similar trend as the transmissivity. Borehole BH2, BH3 and BH4 demonstrated higher values as compared to BH1. This may represent a moderately permeable zone, which point to a semi-confined to confined fractured rock aquifer system with variable permeability

Specific storage (Ss) and storage coefficient (S) are key indicators of aquifer storativity. The ranges revealed are wide in both Ss and S values, suggesting a mixture of confined and semi-confined conditions across the wells. The storage coefficient values from are extremely low, of which may suggest confined conditions within the aquifer system and perhaps a strong reliance on elastic storage. Elastic storage can be referred to as the volume of water that can be released or stored within an aquifer due to the compressibility of both the water and the aquifer matrix, which suggests the behaviour related to a confined aquifer.

Specific capacity (Sc) values were manually calculated via the log-time drawdown graph derived from the pumping test data, provided a direct measure of well performance, where BH2 and BH3 stand out

with values of 0.64 and 0.58 L/s/m respectively. This implies efficient response to pumping and high productivity, while BH4 and BH1 show lower SC values at 0.29 and 0.33 L/s/m respectively, implying moderate transmissivity and conductivity.

Estimation of sustainable yields, derived from the FC Programme, are significantly lower than the initial test discharge rates, underlining the need for controlled groundwater exploitation. BH2 reports the highest sustainable yield at 292.9 m³/day, which reflects a favourable aquifer thickness and transmissivity of 34.7 – 43.95 m²/day. While BH1 shows the lowest yield at 80.3 m³/day, suggesting that it is better suited for small-scale water supply and not commercial use.

The results obtained from the derivative fitting, the AQTESOLV and the FC Programme align with the theoretical expectations under the Cooper-Jacob approximation, a widely used analytical method for interpreting drawdown in confined aquifers under constant-rate pumping which simplifies Theis' non-equilibrium solution for confined aquifers. The method assumes radial flow to a well in a homogenous and isotropic aquifer, which allows for the estimation of transmissivity and storage coefficient from semi-log drawdown data. The use of this approximation must be approached with caution when dealing with a heterogeneous aquifer like the study entails.

To summarize, the methods and analyses applied proved effective in characterizing the aquifer behaviour of the study area. It provided realistic estimates for transmissivity, hydraulic conductivity, and safe abstraction rates, supporting sustainable groundwater development and planning in the fractured metacarbonate terrain. The aquifer system is heterogeneous, with varying degrees of productivity. This variation reflects a fractured rock aquifer system where lithology, fracture density, and degree of weathering significantly influence hydraulic behaviour (Kruseman & de Ridder, 1991). BH1 was significantly less productive, while BH2 and BH3 emerge as the most promising in terms of yield and aquifer response which is likely representing zones with well-developed secondary porosity through fractured zones.

4. CONCLUSION AND POLICY RECOMMENDATIONS

Study Conclusions

The constant pumping test confirmed the diverse hydraulic properties of the aquifer confirming that the Ntanisha wellfield is developed within a heterogeneous fractured metacarbonate aquifer characterized by significant spatial variability, showing BH2, BH3 and BH4 to have higher transmissivity, hydraulic conductivity, sustainable yield and specific capacity. However, BH4 showcased a higher drawdown, but showed promising potential. BH1, on the other hand, displayed the lowest values, suggesting reduced permeability and storativity rendering it only suitable for small scale water extraction.

Sustainable yields estimated using the Flow Characteristic method are consistently lower than constant-rate test discharge values, indicating that short-term pumping rates should not be directly adopted as operational abstraction limits in fractured aquifer systems. The results demonstrate the importance of

borehole-specific abstraction strategies.

The analysis further reaffirmed the importance of applying multiple analytical techniques, such as the FC programme and the AQTESOLV estimating parameters. Though, the conclusion rests on aquifer behaviour rather than method preference.

Study Recommendations

1. Strengthen groundwater regulation and abstraction management via the Water Resources Management Authority (WARMA) by incorporating sustainable yield assessments and periodic pumping test evaluations into groundwater abstraction licensing and compliance monitoring for wellfields run by utilities and municipalities. This will ensure that licensed abstraction rates remain consistent with aquifer response and support long-term groundwater protection.
2. Lusaka Water Supply and Sanitation Company limited (LWSC) should operate the Ntanisha wellfield using borehole-specific abstraction schedules based on sustainable yields determined by the Flow Characteristic (FC) method rather than applying uniform pumping rates across all production boreholes. Periodic optimization of pumping schedules should be undertaken to minimize excessive drawdown and distribute abstraction according to individual borehole productivity.
3. Establish a comprehensive groundwater monitoring programme of groundwater levels. This programme should be maintained through the existing telemetric monitoring borehole, complemented by monthly measurements of static water levels, abstraction volumes and borehole recovery. In addition, periodic water quality monitoring should be undertaken to detect any deterioration associated with long-term abstraction and to provide an early warning of aquifer stress.
4. Integrate multi-method aquifer characterization into future groundwater development in fractured metacarbonate environments so as to include comprehensive pumping test programmes comprising step-drawdown, constant-rate and recovery tests analyzed using complementary methods such as the Cooper–Jacob method, AQTESOLV and the Flow Characteristic method. This integrated approach will improve hydraulic parameter estimation, sustainable yield determination and wellfield design.

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