Water SA 50(1) 131–136 / Jan 2024
https://doi.org/10.17159/wsa/2024.v50.i1.4073

Technical Note

On the Flow Characteristics (FC) method for estimating sustainable borehole yield

M Gomo[1]

[1]Institute for Groundwater Studies, Faculty of Natural and Agricultural Sciences, University of the Free State, PO Box 339, Bloemfontein 9300, South Africa

Flow Characteristics (FC) is one of the few methods developed for predicting long-term sustainable borehole yield of single wells in typical fractured rock aquifers. The FC method uses 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 water strike (fracture) during long-term operations. Since its development, the FC method has been widely applied in many research and consulting projects. Two decades after its development, a review of its technical capabilities and limitations is necessary to enhance understanding among groundwater practitioners while building a platform for further improvements. The main strength of the method is 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. The FC method also caters to the negative influence of impermeable boundaries, thereby enabling planning for different low-yield-causing scenarios. However, the major limitation is in using the subjective closed no-flow boundary without factoring aquifer storativity and the distance of the closed no-flow boundary from the pumping well. Under the influence of the closed no-flow boundary, the water must come from aquifer storage, hence the storativity and the size of the bounded aquifer are very critical parameters. It is therefore incorrect to factor in the influence of the closed no-flow boundary without considering its exact location. This limitation is reflected in the absence of criteria to determine the distance of the closed no-flow boundary from the pumping well for validating the FC results using numerical models. The FC method still needs validation using field operational data; other recommendations for future research are highlighted in the discussion.

CORRESPONDENCE
M Gomo

EMAIL
modgomo@yahoo.co.uk

DATES
Received: 10 March 2023
Accepted: 18 December 2023

KEYWORDS
fractured-rock aquifers
flow characteristics (FC) method
drawdown derivatives
safe borehole yield
sustainable borehole yield
impermeable boundaries

COPYRIGHT
© The Author(s)
Published under a Creative Commons Attribution 4.0 International Licence (CC BY 4.0)

INTRODUCTION

Fractured-rock aquifers are an important source of potable water in many regions of the world. In fractured-rock aquifers, groundwater occurrence and flow are mostly controlled by the presence of connected fractures. An understanding of the groundwater storage and flow properties and their influence on borehole yield is therefore essential to optimise sustainable groundwater production. There is considerable research that has been done over past years to comprehend groundwater flow characteristics in fractured-rock aquifers.

Berkowitz (2002) provides a comprehensive review of approaches to characterise flow and transport processes in the fractured-rock aquifer media. Groundwater productivity in boreholes drilled in fractured-rock aquifers is controlled by multiple factors, such as dyke and lineament orientation and the proximity of surface-water drainage (Holland, 2012). The vertical variation of hydraulic properties with depth has been shown to exert a larger influence on borehole yield estimations in fractured-rock aquifers in comparison to climate change factors (Ascott et al., 2019). Kang et al. (2019) characterised and conceptualized the effects of fracture feature characteristics and geological stress on groundwater fluid flow and transport processes, and developed a Bernoulli CTRW model that can capture non-uniform transport flow in natural fracture networks under the influence of different stress conditions. The influence of faults on regional controls of permeability and the productivity of fractured-rock aquifers has recently been explored by Frederiks and Lowry (2022) with the aid of groundwater numerical models.

Studies on approaches to estimating the sustainable yield of a single well have resulted in the development of several approaches. Van Tonder et al. (2001) developed the Flow Characteristics (FC) method to estimate the sustainable yield of a single borehole in fractured rock aquifers. Piscopo and Summa (2007) proposed the use of prolonged pumping to achieve a constant head to estimate the sustainable yield of the production well in heterogeneous aquifers. Due to the uncertain nature of the factors influencing the estimation of sustainable borehole yield, researchers have continued to advocate for the use of operational data to understand the behaviour of the hydrogeologic system for the estimation of sustainable yield (Misstear and Beeson, 2000; Hammond, 2028). Among these approaches, the FC method (Van Tonder et al. 2001) is the only one that estimates borehole sustainable yield in typical fractured rock aquifers without the need for aquifer parameters.

The FC method uses drawdown and derivatives of drawdown while subjectively factoring in the influence of impermeable boundaries to estimate the sustainable yield of a borehole. The sustainable yield is defined as the operation pumping rate that does not cause the water level in the pumping well to drop below the main fracture/water strike during a prescribed period. To enable easier application, the FC method was programmed into a Microsoft Excel spreadsheet which is known as the FC program (Van Tonder et al. 2013). The FC program also contains other classical analytical solutions for estimating aquifer parameters.

The FC method has become a standard approach for estimating borehole sustainable yield in fractured-rock aquifers, especially in Africa where most of the aquifers are fractured. Due to its simplicity, the method is favoured by many groundwater professionals. The use of the method by researchers is evident in papers and academic theses such as Gert, 2007; Mukendwa, 2009; Grobler, 2014; Setjhaba, 2017; Paxton, 2018; Conrad et al., 2019; and Ndubuisi, 2022. The method is also extensively used by groundwater practitioners in the consulting industry such as Pendragon Environmental Solutions, 2013; Geoss, 2017; DHS Groundwater Consulting Services, 2021; Groundwater Complete, 2021 and JG Afrika, 2022.

However, despite its wide application, a technical review of the FC method to provide insights into its strengths and limitations has yet to be conducted. Considering the role of the method, such a review will improve the understanding of its working principles and practical application. Firstly, an overview of the principles of the FC method is presented. Thereafter a discussion of the strengths and limitations of the FC method is presented, while highlighting aspects that need further improvements.

THEORETICAL BACKGROUND OF THE FC METHOD

The FC method is based on the rationale that the borehole sustainable yield must not cause the water level to fall below the main fracture/water strike during the operational period, to prevent the fracture from dewatering during the prescribed operation time (Fig. 1). The main water strike refers to the highest-yielding fracture/water-bearing zone. When a fracture is dewatered, there's no hydraulic pressure to ensure that the fracture can withstand the overburdened weight. As a result, the fracture can collapse thereby preventing the flow of water to the borehole causing the borehole to dry.

In the FC method, Van Tonder et al. (2001) termed the borehole pumping rate which does not cause the water level to drop below the main fracture/water strike as the 'sustainable yield', which has the same meaning as safe or reliable 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 (Eq. 1).

$$Q_s = Q_p \frac{S_a(t = t_{long})}{S_p(t = t_{long})} \quad (1)$$

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 ($s_{boundary}$) (Eq. 2).

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

The component s_{well} is extrapolated using the Taylor series (only the first 2 terms) around the late-time measurement points of the drawdown at the end of pumping (t = t_{EOP}) (Eq. 3). The two terms in Eq. 3 are the first and second derivatives of drawdown, respectively.

$$s_{well}(t = t_{long}) \approx s(t = t_{EOP}) + \left[\frac{\partial s}{\partial \log t}\right]_{t=t_{EOP}} (\log t_{long} - \log t_{EOP}) + \frac{1}{2}\left[\frac{\partial^2 s}{\partial (\log t)^2}\right]_{t=t_{EOP}} (\log t_{long} - \log t_{EOP})^2 \quad (3)$$

The subjective effect of the no-flow boundaries on the production well ($S_{boundary}$) is incorporated using imaginary wells pumping at the same rate as the production wells. The nature of the impermeable boundaries ranges from single, to parallel, to the closed/square no-flow boundary as the worst case (Fig. 2).

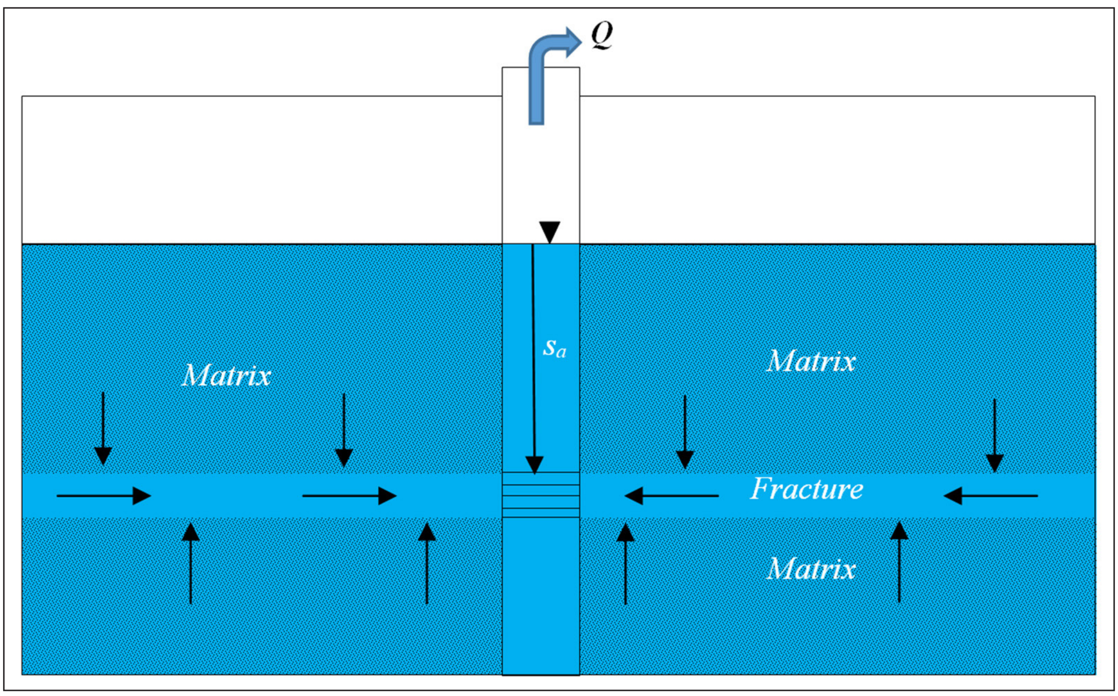

Figure 1. Schematic diagram showing the available drawdown (s_a) above the fracture/main water strike

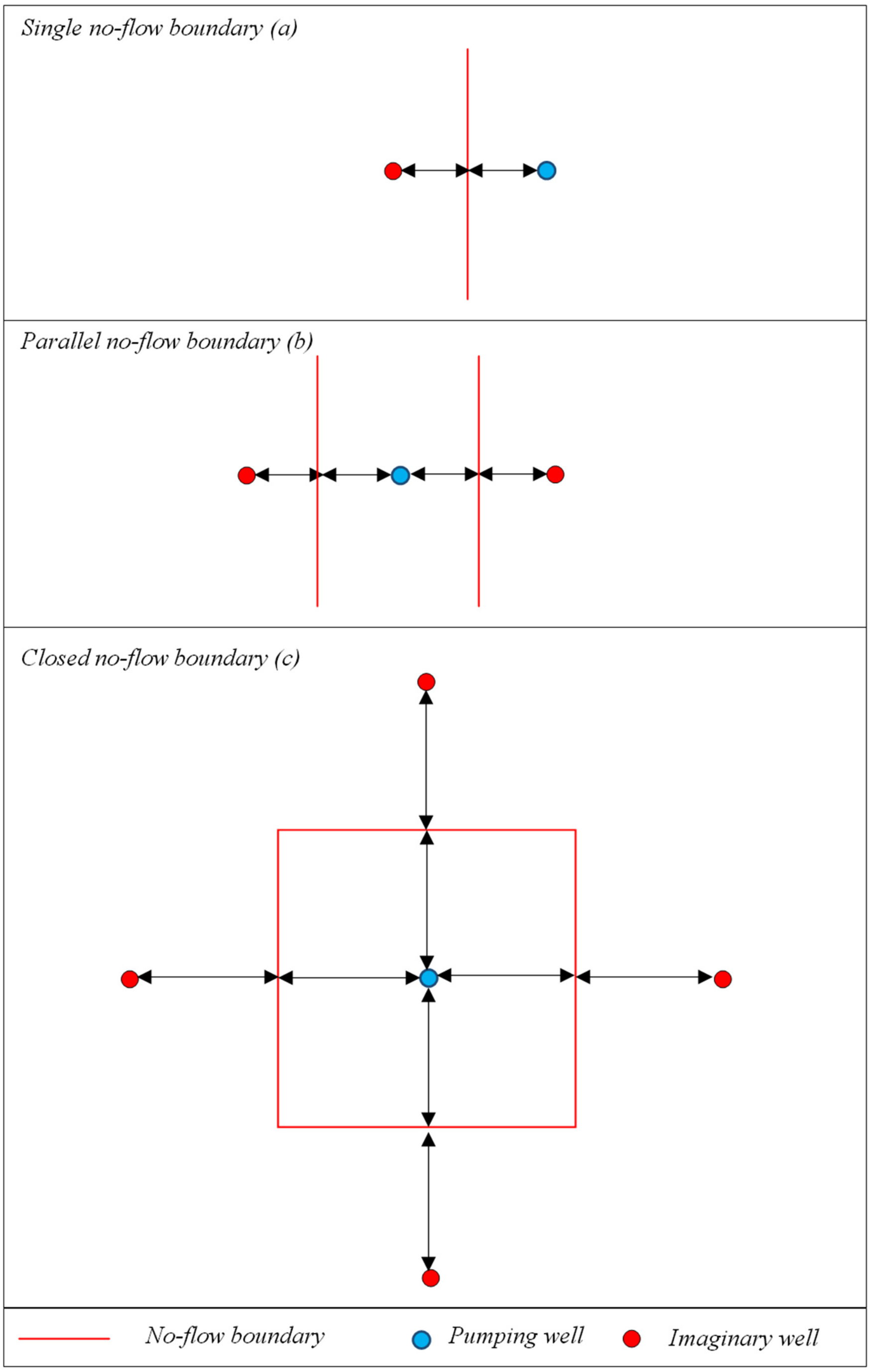

Figure 2. Schematic showing the representation of no-flow boundaries using imaginary wells; distance between the wells and boundaries is equal

The s_a (Eq. 1) is the maximum drawdown that shall not be exceeded after a long abstraction period. This parameter is critical because it basically defines the head of water available for pumping. The FC method recommends that s_a be determined as follows:

- Distance of main water strike from the static water level (if drawdown during pumping test has reached the main water strike).
- Use the geometric mean of the water strike and the end drawdown of the pumping test if the main water strike was not reached during the pumping test.
- When there is no information on water strike positions, consider the position where the drawdown graph shows a sharp increase (inflection points) as a potential indication of fracture dewatering or impermeable boundaries.
- For dolomitic aquifers, 5 m was recommended based on the author's experience.

The FC method offers two types of solutions – the basic and the advanced solution. The basic solution uses drawdown, and derivatives, and subjective information about boundaries which does not require information on aquifer transmissivity (*T*) and storativity (*S*). The basic solution gives an average sustainable yield after taking into consideration the scenarios on: best-case (no boundary influence), single no-flow boundary, parallel no-flow boundary, and closed no-flow boundary as the worst-case scenario.

On the other hand, the advanced solution analyses use both the drawdown derivatives and specific information about the boundary and other abstraction boreholes. The advanced analysis requires input of both aquifer *T* and *S* properties. In the advanced analysis, the estimate of sustainable yield is characterized by the uncertainty that arises from the limited knowledge of the aquifer parameters and the specific location of the boundaries.

However, because of the limited availability of specific information on the boundary and other pumping wells, the basic solution analysis is often employed. A recharge input is also required in the FC method, but the worst-case scenario of no recharge under drought conditions is recommended. The FC method was programmed into the Excel spreadsheet and is freely available from the Institute of Groundwater Studies in South Africa.

DISCUSSION

The FC method is one of the greatest innovations of the 20th century in the science of groundwater hydraulics. The simplicity of the principle, and application in a very practical way to protect the main water strike from dewatering, make it an outstanding method.

The basic solution of the method only uses drawdown and derivatives; it does not need an estimation of aquifer *T* and *S*. This makes the FC method less susceptible to the influence of heterogeneities that typically manifest their effects in the estimation of aquifer parameters because they cause deviation of drawdown data from the theoretical models. The influence of uncertainties associated with aquifer parameter estimation is also eliminated. The heterogeneities do not affect how the method is used but are rather reflected in sustainable borehole yield estimate which is the desired result because it captures the nature of the tested radius of influence.

The advanced solution of the FC method uses aquifer *T* and *S* to cater to the release of water from storage and the flow of water between the pumping well and the specified boundaries and/or other production wells in the study area. The *T* and *S* properties are calculated in the FC method using the generalized Theis (1935) radial flow model. However, this does not make the FC method an appropriate approach to estimate *T* and *S* in typical fractured-rock aquifers. The meaning and use of these parameters are therefore confined to the estimation of the sustainable yield in the FC method.

The FC method uses a single-well test where drawdown is measured and monitored during the test and long-term operation in the pumping well. While the idea is to protect the fracture from dewatering during long-term pumping, the fracture receives most of its water from the surrounding aquifer matrix which acts as a storage reservoir. Monitoring in the pumping well provides a response to the fracture which is the flow path but does not capture the matrix aquifer response. The matrix aquifer is the main storage media sustaining the fracture during the long-term pumping operation of the borehole. Some form of monitoring and analysis is, therefore, necessary in the matrix to understand the impact of pumping and the recharge processes.

The incorporation of the influence of no-flow boundaries helps to prepare for the worst-case scenario beyond the tested space and time. Planning and preparing for the worst-case situations is needed in any form of the production industry. However, there are some limitations with the boundary solution that are noteworthy. When the single and parallel no-flow boundaries are factored in, the pumping well receives water through the non-bounded sides and from the storage. The situation is however different for the worst-case scenario of the no-flow closed boundary because this boundary completely cuts off all lateral flow to the pumping well. Without any lateral flow to the pumping well, storage and recharge are the only sources of water to sustain the pumping. In most of the evaluations with the FC method, a recharge of zero is used as a worst-case scenario of drought conditions. This implies that when a closed no-flow boundary has an effect, all the pumped water must now come from storage throughout the prescribed operation time of the borehole. The volume of water in storage is influenced by the size of the aquifer which is a function of the distance between the pumping well and the no-flow closed boundary. When the no-flow closed boundary is located closer to the pumping well the volume of water in storage to sustain the pumping is less than when the closed no-flow boundary is located at a distance. It is practically difficult if not impossible to incorporate the future no-flow influence of boundaries without considering the time and space in which they will occur.

The effects of the no-flow closed boundaries are incorporated using imaginary wells located on each side of the boundary while abstracting at the same rate as the pumping well. The imaginary well uses the principle of superposition where the effective drawdown in the pumping well increases according to the number of imaginary wells and not according to the volume of the aquifer under consideration, which is a function of the location of the pumping well from the no-flow boundaries. The problem of no-flow boundary representation can be seen when attempting to use a numerical model to validate the sustainable yield estimate from the FC method. The challenge is further demonstrated during the development of the method, where the validation was done as follows (Van Tonder et al., 2002 p. 98 Part B):

> *Two-layer generated pumping test (2 020 x 2 020 m square closed boundary) with typical parameter values for fractured aquifers in the Karoo rocks of Southern Africa with a fracture zone in the bottom layer. The MODFLOW program was run for a period of two years with an abstraction rate of 2 L/s. The generated data for times up to three days (i.e. the typical length of a pumping test) were used in the FC method to estimate the drawdown and sustainable yield by extrapolating the drawdown to two years. The correct answer is of course 2 L/s.*

A few concerns can be raised about the numerical validation that was conducted for the FC method. Firstly, the rationale for placing the closed square no-flow boundary at 1 000 m from the pumping well at the centre of the model is not provided. This is important because one will need to know the criteria to choose the distance of the no-flow boundary from the pumping well that is sufficient to provide aquifer storage that is able to sustain the pumping well over the long term. In this case, the 2 000 m by 2 000 m boundary appears to have been arbitrarily selected. This raises a challenge for practitioners who may want to perform validation after using the FC method.

Secondly, the validation evaluation does not compare the final drawdown at the end of the 2-year pumping simulation to the available drawdown allocated in the FC method; yet this is the core principle of the method. Thirdly, the pumping rate of 2 L/s used for the constant discharge test is the same rate at which the 2-year MODFLOW simulation was conducted. The idea could have been to first simulate a pumping test numerically in MODFLOW considering that the aquifer is fully stressed but not exceeding the main water strike/fracture. This would be followed by analysing the pumping test data from the model using the FC method to estimate the sustainable yield based on a prescribed available drawdown. Thereafter a numerical model is used to simulate the pumping of estimated sustainable yield for 2 years and to compare the end of pumping drawdown to the available drawdown based on fracture position.

It will therefore be difficult to ascertain whether the 2-year simulated drawdown from pumping with a sustainable yield exceeded the available drawdown or not; yet this is the measure of sustainability according to the FC method. The fact that the 2-year FC extrapolated drawdown was equal to the numerical model simulated drawdown does not imply that the pumping drawdown did not exceed the available drawdown; neither was the yield sustainable.

A closed square no-flow boundary of 2 000 m by 2 000 m was used, with the pumping well located at the centre of the model. The question is what the implication would be if the no-flow square closed boundary was located at say 500 m or perhaps 200 m. With a smaller closed boundary, there will be less aquifer storage, hence a reduced period of sustainability. There's scientific evidence to suggest that there are limitations to the closed no-flow subjective boundaries solution in the FC method.

It is important to reiterate that the FC method was developed to estimate the borehole sustainable yield in typical fractured-rock aquifers. The idea is to protect the fracture which is the main groundwater-bearing bearing feature. A fracture in which the water level/hydraulic head remains above the fracture is essentially a confined aquifer system. It is, therefore, possible to hypothesize that the application of the FC method can be extended to porous confined aquifers using the same principle of protecting the water-bearing confined layer. Future research to evaluate the potential application of the FC method in aquifer systems other than the typical fractured rocks is needed. It is also worth mentioning that the pumping well drawdown was extrapolated using the Taylor series, but no rationale was provided for this choice. It would be important to explore other extrapolation methods and evaluate the effects. Lastly, the absence of operational data to confirm the sustainable yield estimates of the FC method remains a limitation (Hammond, 2018) that needs to be addressed.

CONCLUSIONS

The paper provides a technical review of the FC method used for predicting the long-term sustainable yield of a borehole in fractured rock aquifers. A discussion of the strengths and limitations of the method are presented. The FC method is a simple, yet very effective approach to determining a borehole yield that protects the main water strikes/fracture. Using only drawdown and derivatives, the approach is less susceptible to heterogeneity effects and uncertainties of aquifer parameter estimation.

This paper highlights the limitation of using the subjective closed no-flow boundaries on the FC method without considering aquifer storativity and the influence of the distance of the location from the pumping well which defines the volume of the aquifer bounded by the no-flow boundary. Due to the influence of the no-flow closed boundary, the water must come from storage, which is a function of the aquifer volume bounded by the no-flow boundary. It is therefore incorrect to factor in the influence of closed no-flow boundaries without considering their exact location. The limitation is clear when trying to validate a sustainable yield estimate from the FC method using numerical groundwater flow modelling. There are no criteria to determine the distance of the no-flow closed boundary from the pumping well that will enable pumping in a sustainable manner. This makes it difficult for practitioners who may want to validate their findings from FC using numerical models.

These limitations do not, therefore, suggest that the FC method approach of subjective boundaries is not useful or should be downgraded. It is important to acknowledge both the strengths and limitations of the approach. Highlighting the strengths promotes a better understanding and wider meaningful application of the method. Understanding the limitations of the approach provides a platform for further research to improve the method.

Future research is recommended to test the application of the FC method in typical porous confined aquifers with the idea of preventing dewatering of the confined aquifer. Other methods can be tested to extrapolate the pumping well drawdown and be compared to the Taylor series approximation.

ORCID

M Gomo
https://orcid.org/0000-0003-3205-3097

REFERENCES

ASCOTT JM, MANSOUR MM, BLOOMFIELD PJ and UPTON AK (2019) Analysis of the impact of hydraulic properties and climate change on estimations of borehole yields. *J. Hydrol.* **577** 123998. https://doi.org/10.1016/j.jhydrol.2019.123998

BERKOWITZ B (2002) Characterizing flow and transport in fractured geological media: A review. *Adv. Water Resour.* **25** (8–12) 861–884. https://doi.org/10.1016/S0309-1708(02)00042-8

CONRAD J, SMIT L, MURRAY K, VAN GEND-MULLER J and SEYLER H (2019) The Malmesbury Group – an aquifer of surprising significance. *S. Afr. J. Geol.* **122** (3) 331–342. https://doi.org/10.25131/sajg.122.0028

DHS GROUNDWATER CONSULTING SERVICES (2021) Water use licence application geohydrological assessment. Port Elizabeth, South Africa. URL: https://ecoroute.co.za/sites/default/files/2022-02/Redhaus_WULA_Geohydrological%20Report_0.pdf (Accessed 24 February 2023).

FREDERIKS SR and LOWRY SC (2022) Predicting permeability in fractured rock aquifers of Northwestern Uganda at a regional scale. *J. Hydrol. Reg. Stud.* **42** 101181. https://doi.org/10.1016/j.ejrh.2022.101181

GEOSS (2017) Borehole yield and quality testing at Croydon Vineyard Estate, Somerset West. Western Cape. URL: https://www.croydonvineyardestate.com/wp-content/uploads/2021/09/GEOSS-Report.pdf (Accessed 5 March 2023).

GERT PN (2007) Geohydrological characteristics of the Msikaba, Dwyka and Ecca Groups in the Lusikisiki Area, Eastern Cape. MSc thesis, University of the Free State.

GROBLER JR (2014) Hydrogeological exploration and characterisation of the aquifers found in Middelburg, Eastern Cape, for town water supply. MSc thesis, University of the Free State.

GROUNDWATER COMPLETE (2021) SALDANHA BULK DRY ORE TERMINAL: Phase 1 Report on groundwater impact assessment. URL: https://enviro-eap.co.za/wp-content/uploads/2021/05/26.APPENDIX_G_Saldanha_Ore_Terminal_Phase_Groundwater_assessment-1.pdf (Accessed 5 March 2023).

HAMMOND PA (2018) Reliable yields of public water-supply wells in the fractured-rock aquifers of central Maryland, USA. *Hydrogeol. J.* **26** 333–349. https://doi.org/10.1007/s10040-017-1639-4

HOLLAND M (2012) Evaluation of factors influencing transmissivity in fractured hard-rock aquifers of the Limpopo Province. *Water SA* **38** (3). https://doi.org/10.4314/wsa.v38i3.3

JG AFRIKA (2022) Geohydrological assessment for cement plant, Lichtenburg, North West Province. URL: https://www.greenmined.com/projects/Lichtenburg/Geohydro%20report.pdf

KANG PK, LEI Q, DENTZ M and JUANES R (2019) Stress-induced anomalous transport in natural fracture networks. *Water Resour. Res.* **55** (5) 4163–4185. https://doi.org/10.1029/2019WR024944

MISSTEAR BDR and BEESON S (2000) Using operational data to estimate the reliable yields of water-supply wells. *Hydrogeol. J.* **8** (2) 177–187. https://doi.org/10.1007/s100400050004

MUKENDWA MH (2009) The groundwater flow regime of the Kombat Aquifer, Namibia. Masters in Geohydrology thesis, University of the Free State.

NDUBUISI GI (2022) Hydrogeophysical characterization of coastal aquifers for solution-based modeling, West Coast, South Africa. MSc thesis, University of the Western Cape.

PENDRAGON ENVIRONMENTAL SOLUTIONS (2013) Ground water assessment implications for mine water management: Deposit C Sherwin Creek Iron Ore project. URL: https://epbcnotices.environment.gov.au/_entity/annotation/784c8052-fd2e-e711-891f-005056ba00a7/a71d58ad-4cba-48b6-8dab-f3091fc31cd5?t=1577404800341 (Accessed 6 March 2023).

PAXTON JN (2018) Hydrogeological investigation of the Rietvlei sandstone, Robertson, South Africa. MSc thesis, University of the Free State. South Africa.
PISCOPO V and SUMMA G (2007) Experiment of pumping at constant-head: an alternative possibility to the sustainable yield of a well. *Hydrogeol. J.* **15** 679–687. https://doi.org/10.1007/s10040-006-0132-2
SETJHABA SIM (2017) Groundwater resource assessment for development and use in Jozini, KwaZulu-Natal. MSc thesis, University of the Free State.
VAN TONDER, BARDENHAGEN I, RIEMAN K, VAN BOSCH J, DZANGA P and XU Y (2002) Manual on pumping test analysis in fractured-rock aquifers. WRC Report No. 1116/1/02. ISBN No. 86845 861X. Water Research Commission, Pretoria. URL: https://www.wrc.org.za/wp-content/uploads/mdocs/1116_1_021.pdf (Accessed 3 April 2023).
VAN TONDER GJ, BOTHA JF, CHIANG WH, KUNSTMANN H and XU Y (2001) Estimation of the sustainable yields of boreholes in fractured rock formation. *J. Hydrol.* **241** (1–2) 70–90. https://doi.org/10.1016/S0022-1694(00)00369-3
VAN TONDER GJ, DE LANGE F and GOMO M (2013) Flow Characteristic (FC) programme for aquifer test analysis. Institute for Groundwater Studies, University of the Free State. URL: https://www.ufs.ac.za/natagri/departments-and-divisions/institute-for-groundwater-studies-(igs)-home/boreholes/free-pumping-test-programme.