Proposed guidelines for the execution, evaluation and interpretation of pumping tests in fractured-rock formations

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Abstract

The main purpose of this paper is to give practical guidelines to every-day groundwater practitioners on how pumping tests should be performed and analysed to obtain proper estimates for questions like: what is the assured yield of the borehole; at what depth must the pump be installed; at what rate could the borehole be operated and for how many hours per day and what are the T- and S-values, etc.?

Introduction

More than ninety per cent of the aquifers in South Africa are fractured aquifers. The conventional type curve analysis procedures (e.g. Theis method of 1935) developed for homogeneous media contain assumptions that are not applicable to field conditions in fractured rocks. Fracture-dominated media cover a wide range of geological materials which, in turn, have a wide variety of infrastructural properties.

For the majority of geohydrological problems, the transmissivity and storativity (together with recharge) are the most important parameters to be determined for the long-term prediction of the behaviour of an aquifer. In practice, the most common methods applied to determine these parameters are from pumping or slug tests. Other methods used to estimate these parameters include:

- rock sampling and laboratory measurements
- analysis of natural variations of water levels (water balance)
- inverse modelling
- correlation with other parameters, e.g. electrical resistance or grain size
- use of environmental tracers
- packer and double packer tests.

During a three-year project to study the exploitation potential of Karoo aquifers, the authors found that the S-values obtained from pumping tests are an order too low, if compared to the S-estimates obtained by means of a groundwater balance and a two-dimensional flow model (Kirchner et al., 1991).

Recently, Bredenkamp and co-workers (Bredenkamp, 1992 and Bredenkamp et al., 1994) demonstrated that the calculated storativities (S-values) in fractured-rock aquifers are a function of the distance between the abstraction and observation boreholes (the larger the distance, the smaller the estimated S-value). Until now, more than 15 fractured-rock aquifers in South Africa show this rather interesting response. A possible explanation for this behaviour will be given in this paper.

In an unreviewed paper, Lachassagne et al. (1989), focused on the determination of the hydraulic conductivity by means of short-duration (less than 72 h) and long-duration pumping tests. They showed that in the case of the short-duration pumping tests, the local transmissivity values are highly variable in heterogeneous media, while for the long duration test an effective mean transmissivity can be calculated.

Matheron (1967) demonstrated that if the flow is macroscopically uniform (approximately parallel flow lines), the average hydraulic conductivity always ranges between the harmonic and the arithmetic mean of the local hydraulic conductivity values. If, in addition, the probability density function of the K-values is log-normal and unvarying by rotation in two dimensions, the average K-value is exactly equal to the geometric mean.

It may be difficult to determine the S-values of secondary aquifers from pumping tests. In a laboratory experiment, La Moreaux et al. (1984) showed that it can take up to six months for a carbonate rock to drain completely, so that the storativity increases with time. Seimons (1990) pointed out that the calculated storativities from short-duration pumping tests in the Marble aquifer, near Otjiwarongo, Namibia, yield underestimated S-values compared to the results obtained from long-duration pumping tests of the aquifer.

De Marsily (1986) demonstrated that in a well-sorted sand 40% of the drainage occurred after the first few hours, but that drainage continued for a period of up to 2.5 years.

Barker and Black (1983) showed that for the application of slug tests in fissured aquifers, the calculated T-values will always be overestimated, while the S-values derived can be in error by a factor ranging from 10^{-6} to 10^{5}.

Walthall and Ingram (1984) found that it was necessary to use multiple piezometers to obtain sensible S-values in a fissured sandstone aquifer.

Jacobson (1978) reported that all models for fractured aquifers lead to drawdowns that can also be found under other conditions than those assumed. In many cases boundaries, differing hydraulic conductivity distributions, leaky aquifers, faults and stratification can all lead to drawdowns that may resemble the curves found for the given models of fractured formations. The drawdowns produced by both the delayed gravity response and heterogeneous non-fractured aquifers are the same as some observed in fractured formations. He concluded that additional information from core samples and drilling logs from an aquifer is needed to help decide which model will best describe the aquifer.

Kruseman and De Ridder (1991) showed that the drawdown curve in a single fracture is similar to the well-known Theis curve

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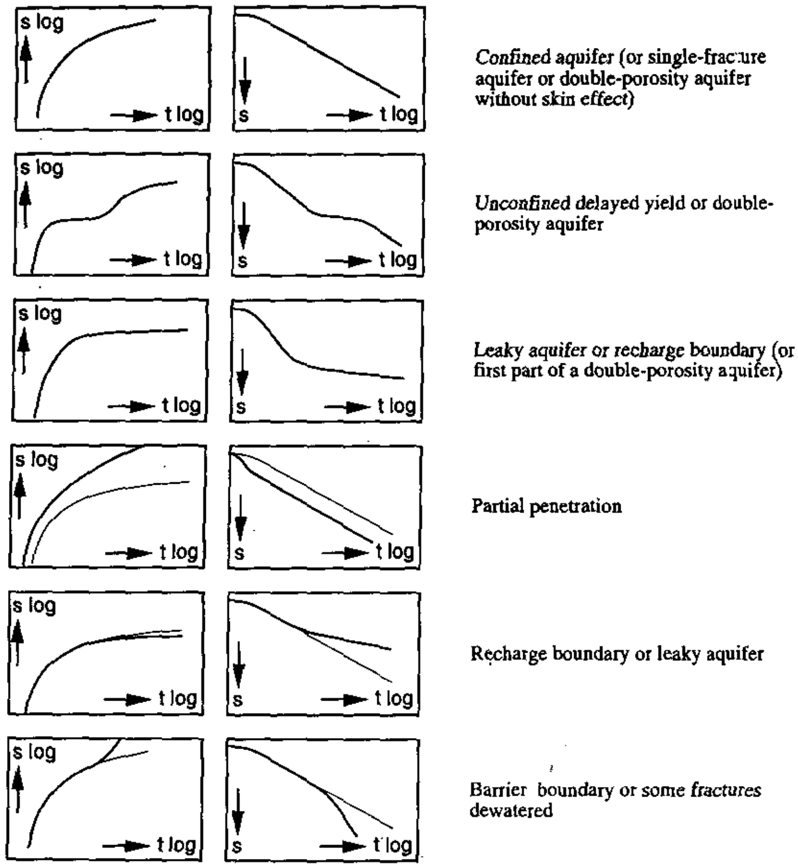


Figure 1
Typical drawdown curves obtained from pumping tests under different conditions. Thin lines indicate the Theis curve and the confined log-normal drawdown curves.

for porous confined media, while the drawdown curve in a double-porosity fractured medium is the same as that in a water-table aquifer of the kind discussed by Neuman (1972). Figure 1 shows different typical drawdown curves that could be obtained from pumping tests under different conditions.

On the campus of the University of the Orange Free State (UOFS), a pumping test terrain has been developed since 1990 for the training of students. This terrain also forms part of a Water Research Commission project of Botha and co-workers (Botha et al., 1994) to study analyses of aquifer tests in fractured formations. On this terrain, 22 boreholes were drilled in an area of 120 m x 120 m. Six of the boreholes have yields in excess of 3 ℓ/s, seven were totally dry during drilling (air percussion drilling), while the yields of the other 9 boreholes vary between 0.5 and 1.5 ℓ/s. Two boreholes situated 2 m apart have yields of 0.2 ℓ/s and 6 ℓ/s respectively (no dolerite dykes or sills are present). This illustrates the heterogeneities associated with fractured-rock aquifers. Three of the boreholes that had been dry during drilling, were test pumped one year after drilling was completed, and both of them have yields in excess of 0.5 ℓ/s. This illustrates the need for borehole development after drilling, because (i) clogging of fractures tends to occur during the drilling process and (ii) some of the fractures may be filled with material like calcite, etc. A complete discussion of results of the study of the UOFS terrain will be given in a report to the WRC by Botha and co-workers (not completed yet).

The main purpose of this paper is to give practical guidelines for every-day groundwater practitioners of how pumping tests should be performed and analysed to obtain proper estimates for questions like: what is the assured yield of the borehole; at what depth must the pump be installed; at what rate could the borehole be operated and for how many hours per day and what are the T- and S-values, etc.?

Fractured media

The term fracture in this paper refers to cracks, fissures, joints and faults, which are caused by:

- geological and environmental processes, e.g. tectonic movement, secondary stresses, release fractures, shrinkage cracks, weathering, chemical action and thermal action; and
- petrological factors like mineral composition, internal pressure, grain size, etc.

From a hydrogeological point of view, a fractured rock mass can be considered a multi-porous medium, conceptually consisting of two major components: matrix rock blocks and fractures. Fractures serve as higher conductivity conduits for flow if the apertures are large enough, whereas the matrix blocks may be permeable or impermeable, with most of the storage usually contained within the matrix. Actually, a rock mass may contain many fractures of different scales. The authors believe that the permeability of the matrix blocks is in most cases of practical interest a function of the presence of microfractures. A rock mass which consists only of large fractures and some matrix blocks with no microfissures (or smaller fractures) is called purely fractured rocks. In this case, the domain takes the form of an interconnected network of fractures and the rock matrix, comprising the blocks surrounded by fractures, is impervious to flow. However, there may still be porosity! In the case where the domain is a porous medium (or a microscaled fractured medium) intersected by a network of interconnected fractures, the rock is termed a fractured porous rock and the domain is therefore characterized by at least two subsystems, each having a different scale of inhomogeneity (called scale effect).

As Fig. 2 shows, fractures originated in three main directions

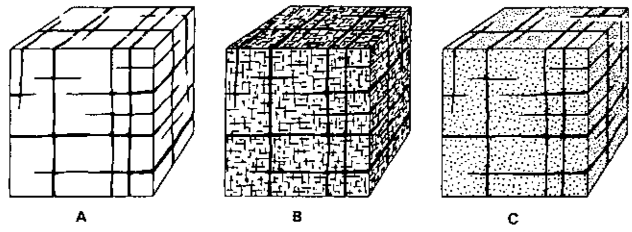


Figure 2
Porosity systems: (A) single porosity; (B) microfissures and (C) double-porosity (after Kruseman and De Ridder, 1991).

and cut the rock into blocks (after Kruseman and De Ridder, 1991). Figure 2A shows the case where the primary porosity of the blocks is near zero (in this case the rock is regarded as a single porosity system). Figures 2B and C show the cases where the blocks consist either of microfissures (B) or porous material (C). Both cases lead to the well-known double-porosity system.

Fractured media may be divided into four categories (Fig. 3, after Streltsova, 1975), depending upon the relative hydraulic properties of the fractures and the blocks or matrix between the fractures.

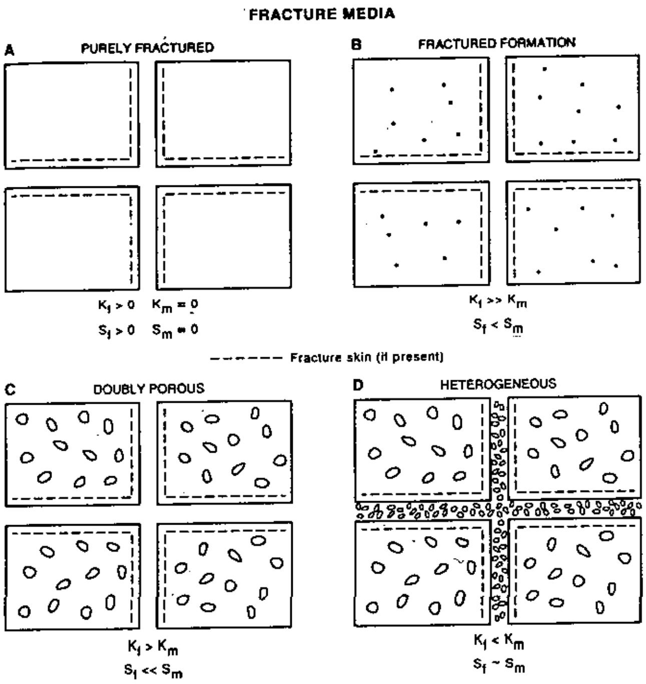


Figure 3
Hydrogeological classification of fractured media (after Streltsova, 1975). K_f and K_m are the hydraulic conductivities of the fractures and the matrix, respectively. S_f and S_m represent the storativities of the fracture and matrix: (A) purely fractured media; (B) fractured formation; (C) double-porosity medium and (D) heterogenous formation. In cases B, C and D the fracture coating (skin) may be significant.

These categories are gradational (Sharp, 1993). In purely fractured media (Fig. 3A) the hydraulic conductivity and water storage are restricted to the fractures, and the rock matrix has virtually no porosity and permeability. Examples may include some igneous intrusive and metamorphic rocks such as granites and gabbros and some volcanic rocks. In many fractured formations (Fig. 3B), the flow is controlled by the fractures while the storage is primarily in the blocks. Examples may include shale, siltstone and sandstone. In the double-porosity medium (Fig. 3C), the relative permeabilities of the blocks begin to approach those of the fractures. Examples may include some sandstones, basalts and carbonate rocks. Finally, Fig. 3D represents a fractured medium in which the fractures have been filled with material that has a lower permeability than the matrix blocks (Sharp, 1993). The so-called skin is a fracture surface which is altered by mineral deposition or coating (usually clay and calcite). In most cases, the permeability of the skin is an order of magnitude less than that of the matrix blocks.

Igneous and metamorphic rocks generally have low matrix porosities. Coarse-grained sedimentary rocks (e.g. sandstone) have relatively high porosities and permeabilities, while fine-grained sedimentary rocks (e.g. shale and siltstone) have relatively high porosities but very low permeabilities. Carbonate rocks have variable porosities and permeabilities, depending on their history.

Fractures may close at depth, due to weight of overlying material and may have different fracture patterns. Many times filling material is found in fractures due to the products of disintegration of the host rocks or the deposition from solutions. A very interesting fact is that fractures usually tend to terminate at other fractures (Berkowitz, 1992).

A fracture set is defined as a group of fractures that lies more or less parallel to each other (Berkowitz, 1992). A fracture system consists of sets of fractures that intersect at a more or less constant angle, whereas a fracture zone is a region containing a cluster of fractures.

The hydraulic conductivities of fractured systems vary considerably and are dependent on: aperture (distance between fracture walls), frequency or spacing (density), length, orientation (random or preferred), wall roughness (asperities, including skin factor), presence of filling material, fracture connectivity, channelling (preferred paths) and the porosity and permeability of the rock matrix. The hydraulic conductivity and discharge of a fracture with smooth parallel walls are respectively proportional to the square and cube of the aperture, as demonstrated by the following equations:

$$K_f = \frac{\rho g}{\mu} \frac{b^2}{12}$$

$$\text{and } Q = K_f b i$$

where:

- b = aperture
- μ = dynamic viscosity
- ρ = fluid density
- g = gravitational acceleration
- i = hydraulic gradient

Maini and Hocking (1977) give the equivalence between the hydraulic conductivity in a fractured medium and that in a porous medium. For example, the flow through a 100 m thick cross-section of a porous medium with a hydraulic conductivity of 0.0086 m/d could also come from a fracture opening not wider than 0.2 mm in a fractured medium with an impervious rock matrix. A porous medium with K = 8.6 m/d and a thickness of 10 m is equivalent to a fracture aperture of 1 mm. This shows the immense importance for the flow of one single fracture (in a rock mass) that is not even wide, e.g. a borehole which intersects one fracture of about 0.6 mm aperture could yield approximately 1 ℓ/s.

The main factor which controls the K-value of an aquifer is the actual size and number of the apertures, although the more fractures of a given aperture present, the greater the permeability of the aquifer (Sharp, 1993).

Theoretical models for fractured aquifers

The flow in fractured aquifers can be explained by various theoretical models. Muskat (1937) was one of the first who analysed the flow in fractured media. Gringarten (1982) reviewed the extensive literature and found that three main types of approaches to the problem are used:

- The deterministic approach, which is based on an accurate and detailed description of individual fracture systems, and is mainly used for small-scale problems in geotechnical engineering.
- The double-porosity medium approach, which assumes a uniform distribution of matrix blocks and fissures throughout the aquifer (including single-fractured models and multi-porosity/multi-permeability models).
- The equivalent homogeneous aquifer approach, which considers only main trends of the pressure behaviour of the fissured aquifer and tries to relate them to a known model of lower complexity.

These theoretical models form the basis of the type curve methods derived by various researchers for the analysis of pumping test data in fractured aquifers. For a complete description of all the different models, the reader is referred to Kotze (1993) and Kruseman and De Ridder (1991).

Barenblatt et al.(1960) introduced the double-porosity concept which has been used extensively in the petroleum field. Two approaches that differ in the manner by which flow from a block to a fissure occurs, have been taken. The first approach assumes that flow occurs under pseudo-steady-state conditions (Warren and Root, 1963); in the other approach, the flow occurs under transient conditions from the block to the fracture (Kazemi et al., 1969). Although the pseudo-steady-state approach simplifies the mathematical computations, it ignores some of the physics of the problem. This implies that the transient approach is clearly superior from a theoretical standpoint. Moench (1984) incorporated the idea of fracture skin (a thin skin of low-permeability material deposited on the surfaces of the blocks, that serves to impede the free exchange of fluid between the blocks and the fracture). The effect of fracture skin in double-porosity systems is to delay flow from the blocks to the fractures and gives rise to pressure responses that are similar to those predicted under conditions of pseudo-steady-state flow (Moench, 1984). According to Moench, by reducing gradients of hydraulic head in the compressible blocks, fracture skin provides theoretical justification for the pseudo-steady-state flow approximations used in the Warren and Root (1963) model. Bourdet and Gringarten (1980) showed that the double-porosity behaviour of a fractured aquifer only occurs in a restricted area around the pumped borehole. Outside that area (i.e. for λ-values greater than 1.78), the drawdown behaviour is that of an equivalent porous medium.

Kruseman and De Ridder (1991) discussed the following methods (Table 1) for the analysis of pumping test data from fractured-rock media:

For a complete description of the first three tests in Table 1, the reader is referred to Kruseman and De Ridder (1991, p. 249). A simplified method of application of the Bourdet-Gringarten method is given by these authors. It is based on matching both the early- and late-time data with the Theis-curve, which yield values of T_f and S_f and T_f and S_f+S_m respectively. The authors recommended the use of this simplified method and found that the method yields reliable values of T_f. We observed, however, that the estimated S-values, as obtained with the simplified method as well as the other methods given in Table 1, still show the distance-dependency as first observed by Bredenkamp (1992) and Bredenkamp et al. (1994).

Figure 4 shows the computed S-values plotted against distance from the pumping borehole at the UOFS pump test terrain (after Botha et al., 1994). In this case, the drawdown curves resemble the well-known Theis curve and the Theis method was used to fit the observed drawdowns at each observation borehole (program AQTESOLV, 1991).

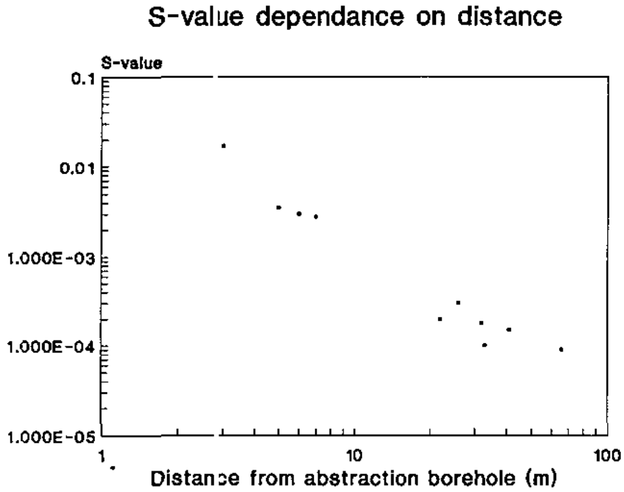


Figure 4
Computed S-values as a function of distance between the observation and pumping boreholes on the UOFS pump testing terrain

Neuman (1994, personal communication) gave the following possible explanation: Consider the rock to consist of nested storage "reservoirs" comprising different scale fractures. At one end of the spectrum are a few large, permeable fractures occupying a small relative rock volume which therefore has small porosity and storativity. On the other end are many small, low-permeable fractures occupying a relatively large rock volume which therefore has large porosity and storativity. Close to the pumping well, pressure in the large fractures declines rapidly relative to its rate of decline in the small fractures. The latter therefore release a relatively large amount of water into the large conductive fractures due to a sizeable local pressure gradient between the small and large fracture reservoirs. Hence S is large. Far from the pumping well, the pressure gradient between the small and large fractures is relatively small. Therefore, water release from the small to the large fractures occurs very slowly. Most of the initial drawdown

TABLE 1
DIFFERENT FRACTURED-ROCK PUMP ANALYSIS PROCEDURES (AFTER KRUSEMAN AND DE RIDDER, 1991)

Method	Assumptions	Parameters obtained (subscript f denotes fractures and m matrix blocks)
Bourdet/Gringarten (1980) (for observation well)	1. Aquifer is confined, thickness of aquifer is uniform, well fully penetrates a fracture; Well is pumped at a constant rate; before pumping the piezometric surface is horizontal; flow to the well is in an unsteady state; 2. Pseudo-steady-state conditions exist in the blocks. 3. $\lambda < 1.78$ ($\lambda = \alpha r^2 K_m / K_f$)	T_f and T_m, S_f and S_m
Kazemi et al., 1969 (for observation well)	1. Same as above 2. Same as above 3. $u^* > 100$	T_f S_f and S_m
Warren-Root (1963) (pumped well)	1. Same as above 2. Same as above 3. Assumes no well losses (skins) and no borehole storage effects	T_f S_f and S_m
Moench (1984) (for pumped and observation wells)	1. Same as above 2. Hydraulic head in blocks is in the transient or pseudo-steady-state 3. Fracture skin may exist	K_f and K_m S_f and S_m (where S denotes specific storage and not storativity) Dimensionless well-bore skin and dimensionless fracture skin

(in the large fractures) at a great distance is associated with water release from storage in the large fractures. Hence S is small.

With time, local pressure differentials between the reservoirs stabilise and flow everywhere within a given radius approaches a steady radial pattern. Therefore, it could be expected that S should approach a uniform value representing both reservoirs. However, as the flow pattern is now essentially stabilised and close to steady state (even though absolute pressures may continue to decline), standard pumping tests may not reveal this fact: the flow is sensitive to S only at early times. If there were only two reservoirs with very different S values, log-log time-drawdown curves close to the pumping well would exhibit a familiar dual-porosity time inflection (of the kind analysed by Neuman (1972) for unconfined aquifers). However, if there is a continuous hierarchy of such reservoirs with a more or less continuous local range of T- and S-values, such inflections cannot be seen. The early log-log time-drawdown behaviour would then just look like a regular Theis curve. Only long pumping tests would reveal deviations from this curve, but unfortunately, storage effects during late behaviour are usually masked by large-scale heterogeneities and boundary effects.

To illustrate the application of his fracture model, Moench (1984) made an analysis of a pumping test in fractured volcanic rock at the Nevada Test Site. He showed that in the absence of fracture skin, the assumption of pseudo-steady-state block-to-fracture flow model does not have a sound theoretical basis. He further urged caution in the use of the standard semi-logarithmic straight-line method (e.g. Kazemi et al., 1969) for evaluating the product of K and aquifer thickness in double-porosity systems. For the pumping borehole, he obtained a K*D-value with his method which is close to the estimated T-value (≈ 285 m²/d) obtained with the standard semi-logarithmic straight-line method. For the observation hole, however, he quoted a value for T = 3 974 m²/d, as obtained with the semi-logarithmic straight-line method. Unfortunately, he did not quote the results for the observation borehole obtained with his method. As the data of the observation borehole were included in his paper, we decided to analyse it by means of the Moench method as coded by Gerachty and Miller (1991). We also analysed the pumping well data with both the Moench and semi-logarithmic straight-line methods. Moench (1984) quoted the thickness of the aquifer as 400 m. Table 2 shows the results we obtained and Figs. 5, 6, 7 and 8 show the best fit solutions if both methods were applied to the pump test data of the two boreholes.

Figures 5, 6, 7 and possibly Fig. 8 clearly show that a good fit was obtained in each case. Very interesting is the fact that the estimated S-values again show distance dependancy as previously discussed. The value of $S_m = 0.5\ m^{-1}$ (specific storativity) obtained in the case of the pumping borehole, clearly is in error because 0.5*400 = 200 (storativity): an impossible parameter value. This strengthens our belief that it is impossible to obtain an S-value

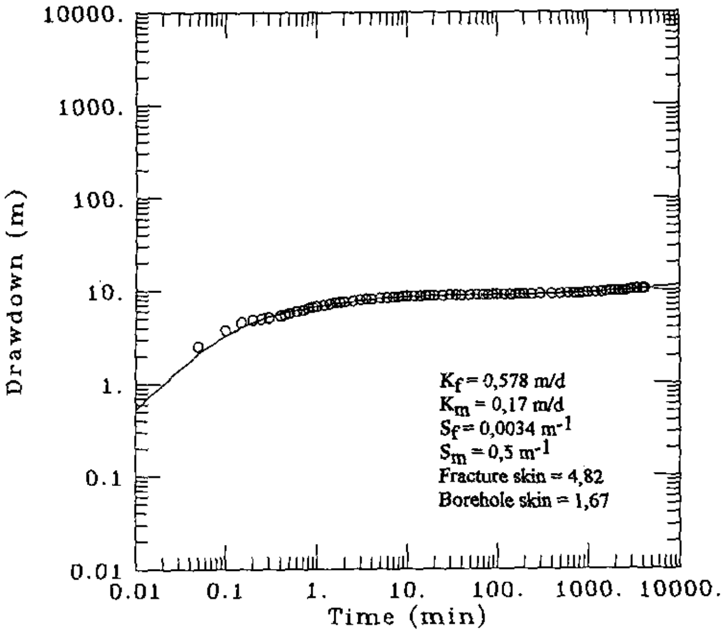


Figure 5
Moench (1984) method applied to the Nevada pumping borehole

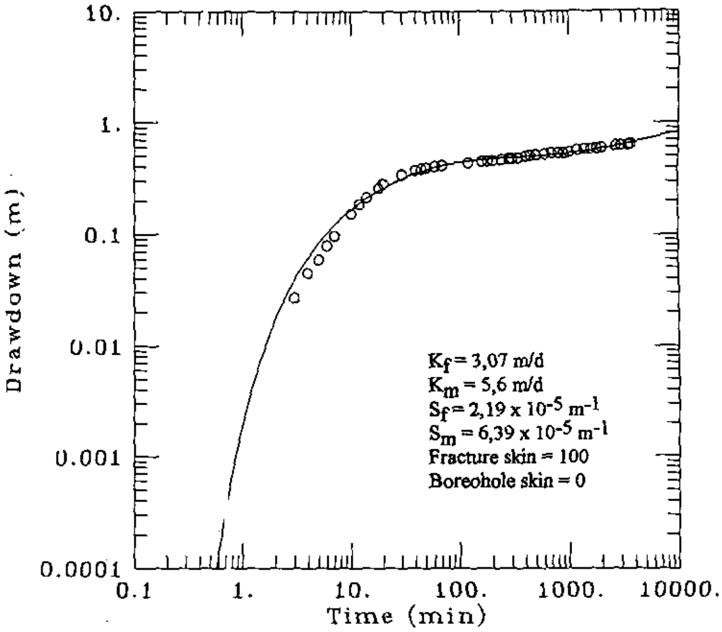


Figure 7
Moench (1984) method applied to the Nevada observation borehole

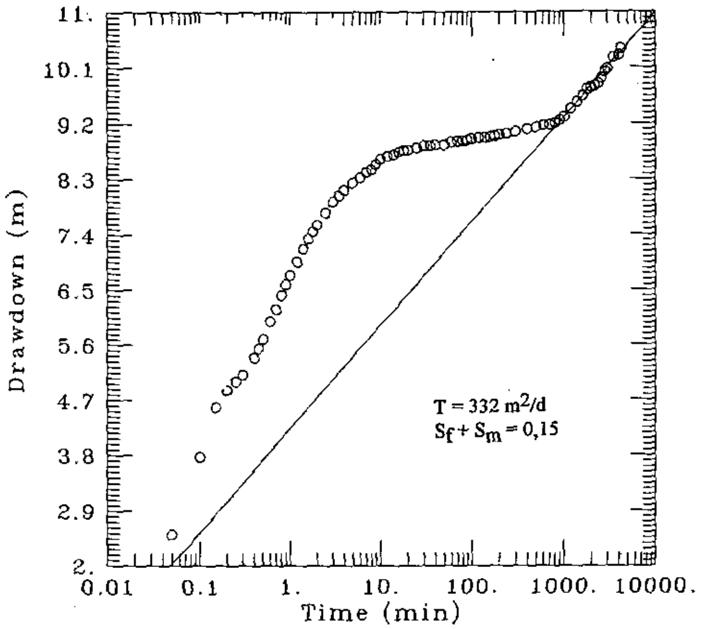


Figure 6
The semi-logarithmic straight-line method applied to the Nevada pumping borehole

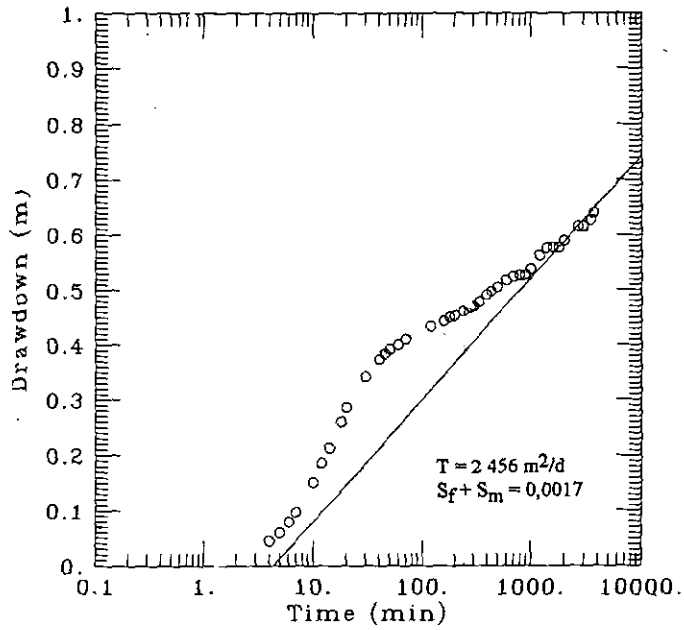


Figure 8
Semi-logarithmic straight-line method applied to the Nevada observation borehole

using data from a pumping borehole alone, unless the actual effective borehole radius is known.

Although the data fits obtained with the Moench (1984) method are indeed excellent, the parameter values obtained must be viewed with great suspicion. The mean square error between the fitted and observed values was 1.2654. We believe that the application of the method needs an experienced user who has a good "feeling" for the correct parameters. When using an automated non-linear least square method (e.g. the Marquardt method as implemented in program AQTESOLV), it is very important that the user supplies the program with logical lower and upper bounds for each parameter to be fitted.

We would like to propose and have the following comments on the interpretation of constant-rate pumping tests in fractured-rock formations:

- For every-day groundwater practitioners, the use of the semi-logarithmic straight-line method is recommended, although for the more experienced users, the Moench (1984) method could be tried if the values of the hydraulic parameters between certain boundaries are known.

- Many of the pumping tests in fractured-rock aquifers will have a drawdown curve which resembles the well-known

TABLE 2 RESULTS OBTAINED WITH THE MOENCH (1984) AND SEMI-LOGARITHMIC STRAIGHT-LINE METHOD		
Borehole	**Parameters obtained with Moench (1984) method**	**Parameters obtained with semi-logarithmic straight-line method**
Pumping hole	K_f = 0.578 m/d (i.e. T = 231 m^2/d) S_f = 0.0034 m^{-1} S_m = 0.5 m^{-1} Fracture skin = 4.82 Borehole skin = 1.67	T = 332 m^2/d S_f+S_m = 0.15
Observation hole	K_f =3.07 m/d (i.e. T = 1 228 m^2/d) S_f = 2.19x10^{-6} m^{-1} S_m = 6.39x10^{-5} m^{-1} Fracture skin = 100 Borehole skin = 0	T = 2 456 m^2/d S = 0.0017

Theis curve. This is not an indicator that we are **not** dealing with a double-porosity medium: On the contrary, drawdown curves in a double-porosity aquifer in which (i) the fracture walls are not coated with some material (i.e. have no skin effect), or (ii) with matrix blocks having permeabilities which are not very much lower than those of the fractures, or (iii) where there is a continuous hierarchy of storage reservoirs with a more or less continuous local range of T- and S-values, early log-log time-drawdown behaviour would look just like a regular Theis curve.

- For a first qualified guess of the T-value of a pumping borehole, the following empirical equation can be used:

$$T = 10*Q \qquad (1)$$

where transmissivity T is in m^2/d and borehole yield Q is in ℓ/s.

The equation above has proved to be surprisingly accurate (on average 75%) in the practical tests we have performed.

- Shallow fractures are often characterised as unconfined or partially confined, although individual fracture sets are assumed to function locally as confined aquifers until they are dewatered by excessive drawdown. Assuming we have a sand aquifer with boulders as depicted in Fig. 9, the definition of whether this aquifer is confined or whether it is a water- table aquifer is a matter of scale: When water is struck in the sand below the boulder, water rises to the piezometric water level. During early times of pumping, the reaction of the aquifer will be that of a confined aquifer. Within a short time, the response will, however, be unconfined. Likewise, we start with homogeneous aquifer reaction. When the cone of depression reaches the second boulder, a boundary is reached, i.e. the aquifer is not infinite in extent. Once the cone has extended so far that the composition within the cone of abstraction becomes respresentative of the whole aquifer, we again approach the homogeneous aquifer response. Similarly (Fig. 10) a borehole that has struck a fracture in a low permeability rock, will have a piezometric water level and display confined aquifer characteristics during very early pumping. At Point A(Borehole 1) in Fig. 10 we have a piezometric level caused by the pressure in the fracture, but in Borehole 2 (Point B), a water level exists. Once the cone of depression reaches the intersection of the fracture with a more permeable water-bearing layer, we have an open system which will react like a water-table aquifer. We believe that in most cases of shallow fractured-rock formation (say less than 100 m beneath ground surface), we have fractures that are locally confined but the aquifer is linked to an open system on a scale which we are usually interested in for management purposes. Our belief is strengthened by the fact that in most fractured-rock aquifers in South Africa, the water level follows the topographic surface. This implies that the system must be open, because we can see no reason for an actually confined aquifer to follow this behaviour.

- For the execution of a pumping test, the reader is referred to **Appendix A**, which gives a complete description of how we propose that a pumping test should be performed in the field. The duration of a constant-rate pumping test is very important. The longer this test, the more emphasis can be placed upon accurate interpretation of results. Unfortunately, cost is a problem when conducting long-duration pumping tests.

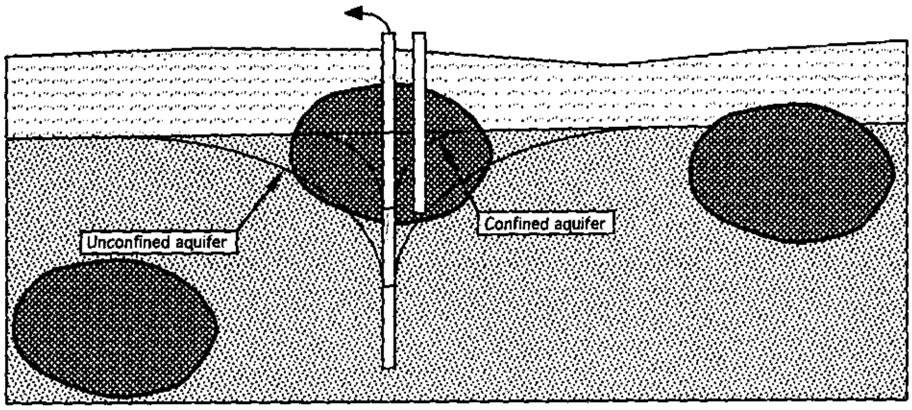


Figure 9

Graph showing that whether an aquifer can be classified as confined or unconfined is a matter of scale

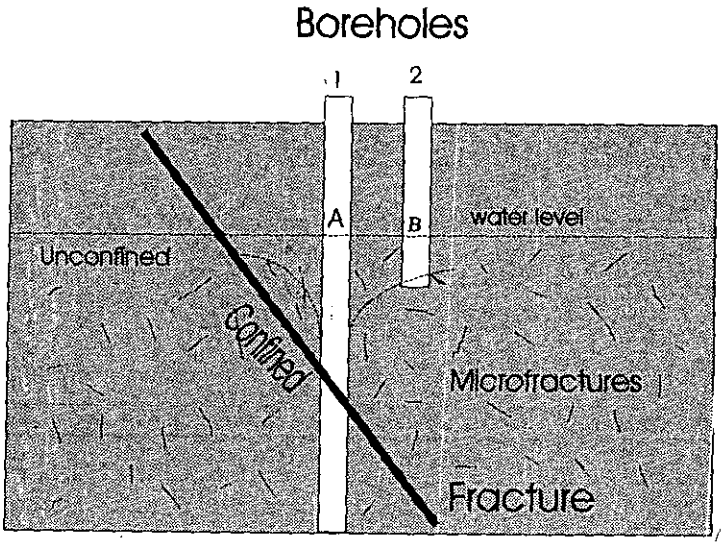


Figure 10
Locally, individual fractures can be classified as confined on a very small scale

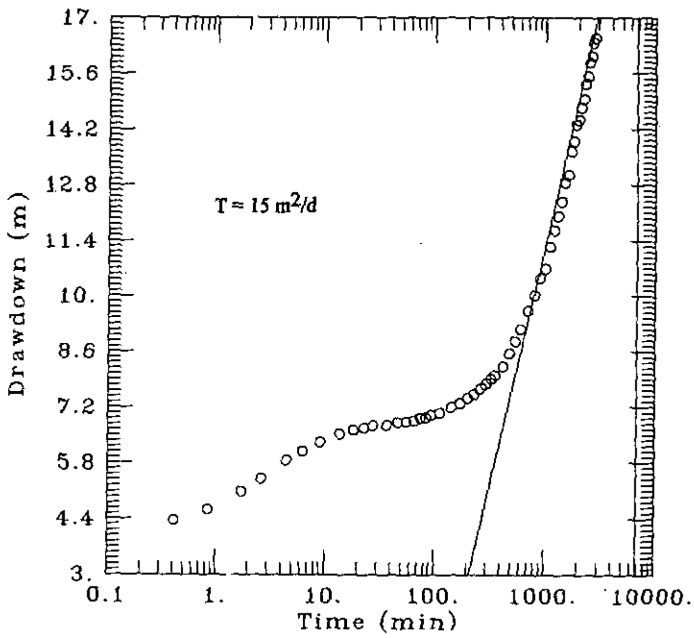


Figure 11
Semi-logarithmic straight-line method applied to the Kokstad pumping borehole

- The following example shows how we propose that a constant-rate pumping test should be interpreted for management purposes:

Locality	:	Kokstad Municipality
Geology	:	Karoo sandstone and shale
Depth of borehole	=	60 m
Water strike	=	45 m
Water level	=	7.22 m
Pump set at	=	51 m
Available water above fracture	=	37.8 m
Blow yield	=	17 ℓ/s

Solution:

The drawdown curve obtained during the constant-rate pumping test is shown in Fig. 11. From this curve, it is evident that we are dealing with a double-porosity aquifer (the drawdown curve starts to flatten after 10 min). The drawdown per log cycle is about 1 m during early pumping and 8 m during late pumping, which clearly indicates that the effect that we are seeing at later times is not due to the presence of a boundary like a dyke. If it had been due to a boundary effect, the drawdown per log cycle would have been, at most, doubled.

From the estimated blow yield of 17 ℓ/s, we made a qualified guess of the transmissivity at early times by using the formula $T = 10*Q = 170\ m^2/d$. A fit of the Theis curve to the early time data yields a value for T of 144 m^2/d which indicates that our first guess of transmissivity was about 18% in error.

We used the semi-logarithmic straight-line method to fit the late drawdown data (see Fig. 11) and obtained a T-value of 15 m^2/d and an unrealistic value for S of higher than 1 which again shows that it is not good practice to calculate an S-value from drawdown data of the pumped borehole. The difference between the estimated T-values for the early- and late-drawdown values, is not so easy to explain and a few factors may be causing this effect. First, it is possible that we are dealing with a skin effect of the fractures. It may also be possible that a zone with a lower T-value is reached after some time of pumping or that some of the smaller fractures just beneath the water level were drained completely after a short time of pumping. Whatever the case may be, the part of the curve for the late pumping times is most important for management purposes and we must use the T-value of 15 m^2/d for extrapolated drawdown calculations.

From the information, we see that we have 37.8 m of drawdown available before the water level reaches the main fracture. It is thus very important to operate the borehole at such an abstraction rate that the water level does not drop below this point.

By using the Theis equation and using a T-value of 15 m^2/d and a storativity value S of 0.001 (based on our experience in Karoo aquifers), we calculated that the borehole could be operated at a yield of 333 m^3/d (=3.85 ℓ/s) for a period of 365 d to yield a drawdown of 37.8 m (The drawdown in the pumped hole is not very sensitive to the S-value, e.g. for an S = 0.005, the drawdown would have been 34.9 m and for an S = 0.0005 the drawdown would have been 38.9 m). It is important to remember that the drawdown has been extrapolated to a period of 365 d, although the actual pumping test duration was only 2 900 min. It is, however, felt that by using such a long time (without any recharge), some influences

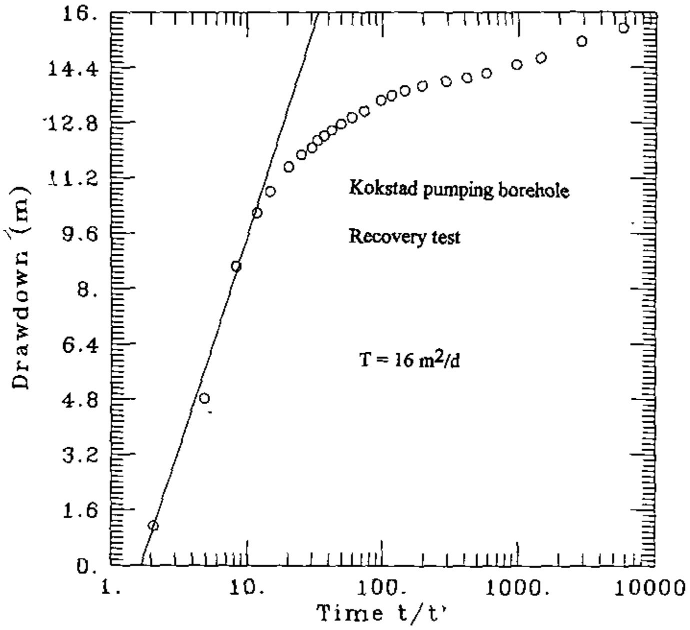


Figure 12
Recovery data for the Kokstad pumping borehole

(e.g. boundary conditions etc.) will be cancelled out. Before actually recommending such an operational abstraction rate, the possible interference of other boreholes on this pumping borehole must be determined via measurements or other methods like flow models. The abstraction rate of 3.85 ℓ/s could be seen as the minimum assured yield of the borehole. The recovery data will show if this borehole could be operated at a higher abstraction rate.

From the recovery data (see Fig. 12) an estimate of the assured yield of the borehole could be made. Theoretically, the residual drawdown plot (s' versus t/t'') should intercept the zero residual drawdown line at t/t'' = 2 if abstraction equals recharge. At this point, "time since pumping started" is twice as long as the "recovery time". Upward displacement of the graph may be observed if either recharge has occurred or the storage coefficient S is different for pumping and recovery (because of e.g. air trapped in the aquifer or delay in time before the elastic deformation of the aquifer has ceased). Downward displacement, i.e. incomplete recovery, is caused by the limited extent of the aquifer.

The interception point can be used to estimate a safe abstraction rate. If, for example, the aquifer is recharged and complete recovery has occurred at e.g. t/t'' = 3, then the pumping time was twice the recovery time. That means the borehole can be pumped for 16 h/d at the same hourly rate that the hole was pumped during the test. Whether the same quantity of water per day may be abstracted at a higher rate in a shorter period depends on the results of the step tests.

A complete recovery at e.g. t/t'' = 1.6 indicates that the abstraction rate of the pumping test cannot be maintained for longer periods. In this case, a recovery time of 24/1.6 = 15 h/d and a corresponding pumping time of 9 h/d must be regarded as more adequate.

For the Kokstad borehole, the pump operated at Q = 13 ℓ/s for a period of 2 900 min. The interception point in this case is at 1.75 which implies that the borehole should recover for 2 900/1.75 = 1 657 min after every 1 243 min of pumping at 13 ℓ/s (or 10.3 h pumping at 13 ℓ/s and 13.7 h recovery during every 24-h day). The total amount of water allowed to be abstracted during a 24-h day is 46.6 m^3/h for 10.3 h; i.e. 482 m^3/d. This implies an abstraction rate of 5.57 ℓ/s for 24 h, which is higher than the rate of 3.85 ℓ/s previously calculated. For the calculation of 3.85 ℓ/s, an extrapolated drawdown after 365 d was calculated that would not cause the water level to drop beneath the main water-yielding structure. No recharge was, however, included in the calculations, and the value of 3.85 ℓ/s can be seen as the minimum assured yield of the borehole. For the Kokstad borehole, we thus recommended an abstraction rate of 5.57 ℓ/s for 24 h/d (or 13 ℓ/s for 10.3 h/d). Whether this abstraction rate could be maintained for a very long period is a question of many unknowns, like recharge and geological boundaries. Only regular water-level observations in the pumping borehole during the operational phase, would indicate if the recommended abstraction rate could be maintained for a long period. If the abstraction rate cannot be maintained, it is important that the time the borehole is operated per day, is scaled down.

Slug tests

The method in which a small volume (or slug) of water is suddenly removed from or poured into the aquifer, is a very convenient method to obtain an estimate of the hydraulic conductivity in a short time.

At the Institute for Groundwater Studies, slug tests are used to obtain a first estimate of the yield of a borehole. Interpretation of a large number of slug tests in different fractured aquifers leads to the empirical graph (Vivier and Van Tonder, 1993; Fig. 13) from which the yield of a borehole can be estimated if the recession time (time from input of the slug until the water level has stabilised again to 90% of its original value) is measured. Figure 13 could be used with good effect to obtain an estimation of the maximum yield of a borehole if no information about the borehole is available. If the slug test analyses showed that the yield may be satisfactory, a complete pumping test should be performed on the borehole.

For the calculation of hydraulic parameters T (or K) and S from slug tests, the reader is referred to the WRC Report of Rudolph et al.(1991).

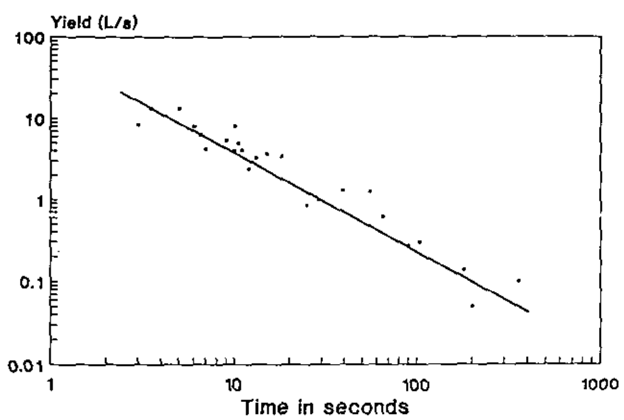


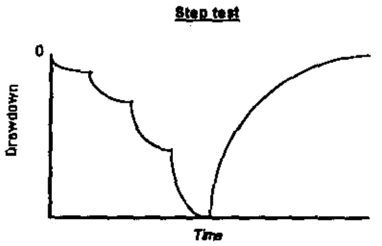
Figure 13
Correlation between the recession time and the yield of a borehole during slug tests

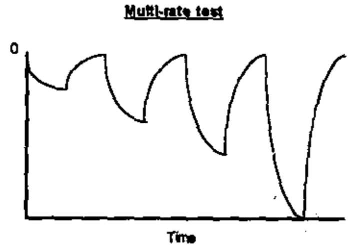
Variable-rate tests

The (short duration) variable-rate tests provide information on the hydraulic conditions in the immediate vicinity of the well.

They allow the determination of:

- the well loss coefficients for an estimate of the efficiency of the well at the operational pumping rate; this coefficient also supplies information on whether the borehole needs (further) development and/or whether it has deteriorated with time;
- the maximum potential of the well, its optimum operating conditions and the specification of permanent pumping installation based on the yield drawdown characteristics;
- the short-term aquifer characteristics.





Two types of variable rate tests can be discerned: the step test and the multi-rate rate test:

Step tests

In step tests, a hole is pumped for a certain period, e.g. 90 min at a constant rate. Thereafter the pumping rate is increased for another 90 min followed by a third, fourth, etc. step of equal duration with the pumping rate stepped up each time. At the end of the last step test the water level is allowed to recover before a constant-rate test begins.

Multi-rate tests

Similar to the step test, the hole is pumped at various rates for periods of equal length. But, differing from the step test, recovery periods of the same duration as the pumping periods are intercalated.

Drawdown in a borehole has two components: formation loss due to friction of the water moving through the aquifer (laminar flow) and well loss caused by turbulent flow near the hole (in fissures, gravel pack, screen and pipes).

For laminar flow, the drawdown s is proportional to the discharge rate Q. In the turbulent flow region it is assumed to be proportional to the pumping rate raised to the power p:

$$s = BQ + CQ^p \qquad (2)$$

where:

B = aquifer loss coefficient
C = well loss coefficient.

A value of p = 2 was originally proposed by Jacob (1946).

For transient flow in confined aquifers, in the absence of well losses, the time-drawdown relationship is after Jacob:

$$s = \frac{2.3}{4\pi T} \cdot Q \cdot \log \left[\frac{2.25Tt}{r^2 S} \right] \qquad (3)$$

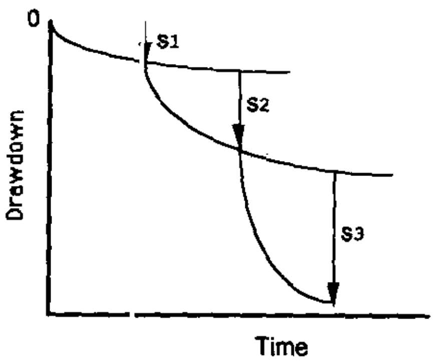
This equation can be applied to unconfined aquifers if the drawdown is small relative to the total thickness of the aquifer. This equation can be written as

$$s = a \cdot Q \cdot \log (b\,t) = QB \qquad (4)$$

with $a = \frac{2.3}{4\pi T}$ and $b = \frac{2.25T}{r^2 S}$

indicating that the aquifer loss is time-dependent. The well loss coefficient is independent of time.

Jacob (1946) used step tests to determine the effective radius of boreholes. He used the incremental pumping rate and the incremental drawdown, caused by the stepped up pumping rates, and determined s_i from extrapolated drawdowns, as shown in the figure below. The well loss coefficient B and the borehole loss coefficient C were determined graphically.



Rorabaugh (1953) used values of the exponent p slightly greater or smaller than 2 to accommodate deviations from the straight line (in the literature values varying between p = 1.5 and 3.5 are found).

Lennox (1966) looked into the validity of the extrapolation of the s-values and found that drawdowns for the third and following steps could not be correctly extrapolated. Bierschenk (1963) simplified the method by dividing the equation $s = BQ + CQ^2$ by Q i.e. $s/Q = B + C \cdot Q$ and plotting the specific drawdown vs. the pumping rate Q.

Clark (1977) compared eight different methods of variable-rate test analysis and found that the results for B, C and T varied little but that only the order of the storage coefficient S could be obtained by these methods.

Brereton (1979) showed the time-dependence of the aquifer loss coefficient B. Non-laminar flow can occur at relatively low discharge rates in fractured-rock aquifers (Mackie, 1982; Atkinson, et al., 1994). Any departure from a constant slope in the s/Q vs. Q plot at higher production rates is the result of changes in the value of the well loss coefficient C, which in turn is attributed to variations in fracture geometry and hydraulic conductivity (Mackie, 1982). Until a recent publication by Helwig (1994), the well loss coefficient C, was taken as independent of time. Helwig (1994), however, proposed that C is time-dependent too and proposed the following general solution for variable-rate tests:

$$s = AQ + (B'Q + C'Q^p)\log t \qquad (5)$$

where:

s is drawdown

Q is discharge

A, B', C' and p are parameters found by curve-fitting or by any optimisation method (note that both B' and C' are time-dependent).

Equation 5 required no preselected duration and incorporates time as an independent variable. Note that if t is constant, the above equation simplifies to the well-known step-drawdown equation.

Mogg (1968) elaborated on the pros and cons of variable-rate tests and made recommendations:

- Multi-rate tests should be carried out instead of step tests because the drawdowns of the second and the successive steps are accurate and not extrapolated. (Multi-rate tests do not take longer than step tests because the water level must in any case recover before the constant-rate test starts. Additional information is gained from the recovery phases).
- There should be steps of equal duration (at least 30 min if the yield is kept constant for the last 25 min) and the pumping rates for the different steps should be approximately Q, 2·Q, 3·Q, etc.
- Although variable-rate tests cannot determine well efficiency but only change in specific capacity with change in discharge rate, useful information can be obtained, e.g. the optimum pumping rate. It is also possible to predict the drawdown at various pumping rates.
- Variable-rate tests should not be used in water-table aquifers unless the drawdown at the maximum pumping rate is small relative to the total thickness of the aquifer.

If T- and S-values are to be determined from variable-rate tests, they should be of a duration that will allow Δs to be determined with sufficient accuracy, i.e. 1 log cycle after the pumping rate has stabilised, i.e. at least 60 min if the pumping rate is stable after ±5 min. Some authors recommend 100 min and even 180 min per step.

Borehole loss factors should be regarded as relative and should only be compared with values obtained from other boreholes drilled nearby and in the same aquifer.

The same holds true for the efficiency calculated as (if p = 2):

$$e = \frac{BQ}{BQ + CQ^2} \qquad (6)$$

because it depends on the value of the aquifer loss coefficient. Boreholes with the same borehole loss coefficient drilled in different formations may therefore have considerably varying efficiencies.

Example of interpretation of a variable-rate test: The Kokstad step drawdown data are shown in Table 3.

Figure 14 shows a plot of the data in Table 3, as well as the best fit obtained with Eq. (5). The following parameter values were obtained by means of a least square method: A=0.00265; B'=0.00117; C'=4.8 x 10^{-9} and p=2.65. The relatively small value for C' in this case is an indicator that the borehole needs no development. Figure 13 shows that these estimated parameters

TABLE 3
DRAWDOWN VALUES FOR KOKSTAD BOREHOLE OBTAINED DURING STEP TEST

Abstraction rate	6 ℓ/s (518 m³/d)	8.7 ℓ/s (751 m³/d)	12.7 ℓ/s (1 097 m³/d)	17.5 ℓ/s (1 512 m³/d)
Drawdown (m) at the end of each 60 min period	2.51	3.98	6.04	8.9

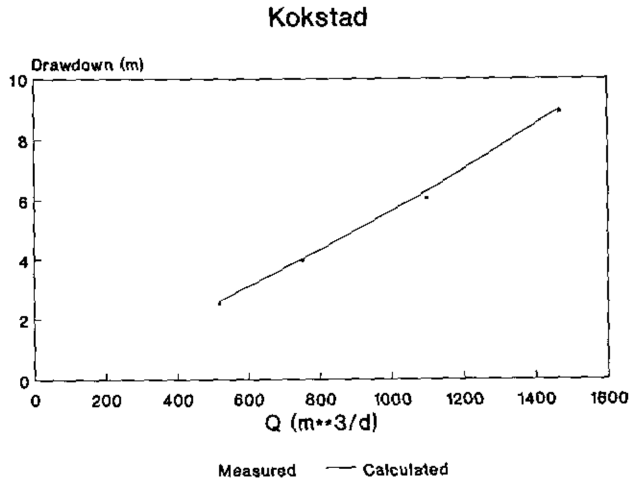


Figure 14
Calculated and measured step drawdown data as analysed with the Helwig method

fitted the observed data excellently. The borehole was pumped at a rate of 1 131 m³/d during the constant-rate test which lasted 2 900 min. By substituting the above parameters into Eq. (5), a drawdown can be calculated for a rate of 1 131 m³/d after 2 900 min. Equation 5 yields a drawdown value of 9.47 m. The actual drawdown measured during the constant-rate test was, however, 16.9 m, which implies that the extrapolated drawdown calculated from the step drawdown test is in error by about 44%. This clearly illustrates the danger to use information of a short test, like a step drawdown test, to calculate drawdown values for a longer period. The reason for the wrong drawdown calculation for the Kokstad borehole with Eq. (5), is clearly that the steeper part of the constant-rate test was not detected during the short-duration step test (it is only after 100 min of pumping that the double-porosity behaviour of the aquifer could be seen). If the duration of the constant-rate test was less than 100 min, the last steeper part of the drawdown curve would also not be detected, and the calculated T-value would be too high. This clearly illustrates the importance of carrying out a long-term constant-rate pumping test. It is, however, felt that the longer the pumping test, the more emphasis could be placed on the calculated parameters, thus lessening the chance of wrong interpretations. This also illustrates the importance of water-level measurement during the actual operational phase of the borehole.

We propose that data of a variable-rate test should only be used to calculate the rate at which the constant-rate test should be performed, and to see if the borehole needs development (a relatively large C- or C'-value is an indicator of this).

Summary

One or more of the questions below are typically asked if a borehole or a well field is developed. The methods that may yield an answer to the questions are also shown.

How much water? (constant-rate test)
How many boreholes? (constant-rate test)
Are they properly developed? (variable-rate test)
What is the optimum pumping rate? (constant-rate and recovery test)
What is the maximum daily abstraction? (recovery test)
First estimate of the yield and K-value of a borehole? (slug test)

Many of the pumping tests in fractured-rock aquifers will have a drawdown curve which resembles the well-known Theis curve. This is not an indicator that we are **not** dealing with a double-porosity medium: On the contrary, drawdown curves in a double-porosity aquifer in which (i) the fracture walls are not coated with some material (i.e. have no skin effect), or (ii) with matrix blocks having permeabilities which are not very much lower than those of the fractures, or (iii) if there is a continuous hierarchy of storage reservoirs with a more or less continuous local range of T- and S-values, early log-log time-drawdown behaviour would just look like a regular Theis curve.

To obtain the correct S-value of a fractured-rock aquifer from a pumping test, still remains a problem. Practical experience by the authors shows that an S-value obtained from an observation borehole which is situated between 5 and 10 m from the pumping borehole in Karoo formations, led to a reliable S-estimate, if compared to the S-value obtained from water-balance studies. The solution for obtaining a reliable S-value from short duration tests may lie in the use of a 3D-groundwater flow model and/or the use of tracers, but the authors have not investigated either of these two options yet.

For management purposes, it is very important to know the depth to the fracture where water was struck. Without this information, it may be very difficult to make proposals about the abstraction rate at which the borehole should be operated.

It is always dangerous to calculate an extrapolated drawdown in a pumping borehole without knowledge of the behaviour of the water levels over a period of time during the operational phase. A good water-level monitoring network is thus vitally important for proper management of a wellfield.

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Appendix A
Guidelines for the execution of pumping tests

Preparations

Obtain information regarding the test hole(s) from the geohydrologist, i.e.:

1. Number
2. Location
3. Depth
4. Diameter
5. Water level
6. Yield
7. Equipment
8. Discharge distance

Get information regarding the observation hole(s), i.e.:

1. Number
2. Location
3. Depth
4. Diameter
5. Water level
6. Equipment

Get information regarding the observation that must be made, i.e.:

Number of step tests and pumping rates
Duration of main test and pumping rate
Duration of recovery test

Times when yield must be measured
Times when water samples must be taken
Times when temperature must be measured
Times when electrical conductivity must be measured
Other measurements

Obtain all necessary equipment:

Test pump(s), pipes, water-level meter(s), water-level recorder(s), flow measuring devices, conductivity meter, thermometer, stop-watch, measuring tape, sample bottles, surveying instruments, etc.

Check that everything is in good working condition. Don't forget:

Notebook, recorder charts, graph paper, ink, pencils, felt pens, etc.

On-site

Report to the owner(s) of the test and observation holes or the person(s) responsible and obtain all information regarding:

Physical dimension of holes, equipment, water levels, yields, water abstraction, water-level response to seasons, rainfall, drought, pumping of holes nearby, etc.

Compare with existing information and write down new data. Obtain permission to open boreholes, remove equipment, etc.

Measure **water levels** (possibly repeatedly, if the water levels are still recovering) in all holes concerned, **depth(s), dia. of casing** and **collar heights** above ground. Note the point from which water-level measurements are taken (normally the highest point of innermost casing). Make a sketch showing the pumped and the observation holes as well as other not measured holes nearby and determine their distance from the pumped hole. Determine the elevation above sea level (or datum level) of all holes measured. Show distance and direction of prominent landmarks in the direct vicinity or describe the test site well. An indication of the true north direction and numbering of all boreholes on the sketch is necessary to enable correlation with the other information. Alternatively, determine the positions using satellite technology.

Insert test pump (and pipes for electrical depth gauge). Make sure that the water pumped will be discharged at a point sufficiently far away from the pumped hole to prevent recirculation.

Install recorders, where necessary. NB: Date, time and water level must be written on the charts when they are put on and when they are taken off. Mark the beginning and end of the graph. The scale of water level and time axis must also be shown and the direction of rise (or fall) be indicated on the charts.

Date and time of the start of the test must be noted, including which hole is pumped and what type of test it is (Step 1, Recovery Step 3, Main Test, etc.). Note the number of the hole measured and its water level directly before each test starts.

Water-level measurements in the pump- and observation holes must be taken approximately at the following times after the start of the test (in minutes after pumping started or stopped).

1	15	75	360 (6h)	1 440 (24h)
2	20	90	420 (7h)	1 800 (30h)
3	25	120	480 (8h)	2 160 (36h)
5	30	150	600 (10h)	2 520 (42h)
7	40	180 (3h)	720 (12h)	2,880 (48h)
10	50	240 (4h)	900 (15h)	3 600 (60h)
12	60	300 (5h)	1 080 (18h)	4 320 (72h)

The pumping rate must be checked, noted down (and adjusted, if necessary) after approximately 7, 15, 30, 60, 120 and 180 min. From then on it should be checked whenever the water levels are measured. Variation of the pumping rate of up to ± 5% is acceptable. Short interruptions (of say 1% of the total duration of the respective test) can be tolerated unless they occur in the early stages of a pumping test. If pumping is interrupted for longer periods, the test has to be abandoned and must be repeated.

Multi-rate tests

Step 1: Pump during the first step test of 60 min at a rate of approximately 1/3 of the expected operational yield of the hole. Measure the water levels at the times stated above. Depending on the distance, measurements in the observation holes can begin at slightly later times. Check that the pumping rate is constant, note down deviations together with date and time.

Take a water sample for chemical analyses (1 ℓ) ± 10 min after the beginning of the first test; (get special instructions if samples for isotope determination etc. are required). Stop the pump after 60 min and measure recovering water levels at intervals stated above, i.e. after 1, 2, 3 min, etc.

Step 2: Pump again for 60 min at a rate of ± 2/3 of the expected operational yield and let the water level recover for a further 60 min. Repeat drawdown and recovery measurements as during the first test. A water sample is generally not required. Check the conductivity, however, and take a water sample if the conductivity has changed noticeably.

Step 3: As for Step 2. The pumping rate should be equal to the expected operational yield.

Step 4: As for Steps 2 and 3. The pumping rate should be approximately 1.25 to 1.5 times the expected operational yield. Take a water sample for chemical analyses at the end of this step.

With multi-rate testing, pumping rates may also be reduced during any of the steps. During the test with the highest pumping rate, the water level should not reach the pump intake.

Main test

The decision of how long a borehole should be pumped during the main constant-rate test depends upon the degree of certainty that is required regarding the sustainable yield of a borehole or a pumping scheme. This decision is generally influenced by the total cost of the scheme and the acceptable risk of failure. For low risks and low capital expenditure schemes, a 24-h test is acceptable. For larger schemes the duration of the main test should be at least 72 h. The pumping rate for the main test must be chosen so that the pumping water level during the test period is not drawn down to the intake of the pump.

Allow sufficient time for the water level to recover after the multi-rate tests. This is generally the case if the hole has recovered overnight and the water level is within a few centimetres of the original rest water level.

The water level and other measurements must, again, be taken according to the schedule outlined above. Temperature and conductivity readings must be taken at least at 12-h intervals. A water sample must be taken after ± 10 min of pumping and another one just before the end of the main test (NB: hole number, date and time of sampling must be indicated on the bottle). Further samples should be taken if noticeable changes in the conductivity are noticed. If the conductivity is not monitored, water samples should be taken at 6-h intervals to allow later measurement in the laboratory and chemical analyses if necessary.

It is a good practice to plot water levels on semi-log graph paper (the time is plotted on logarithmic scale). If considerable changes in the gradient of the curve are noticed, it may be considered to extend the duration of the test so that a few more measurements will allow the determination of the new gradient.

Recovery test

This test must never be omitted. Evaluation of the recovery data can be used to confirm the aquifer parameters determined from the main test. The recovery of the water level should be measured for a period equal to the duration of the main test or until the water level has fully recovered, whichever occurs first. The measuring times must again be according to the above schedule.

One can start with the removal of the pump from the borehole approximately 2 h after the pump has been shut down.

At the end of the recovery period, the recorders can be removed. All holes must be properly closed again or the original equipment be put back again. Rubbish must be collected and the terrain be cleaned up neatly before leaving.