Flow and Transport Characteristics of Groundwater in Karoo Formations

When cool drink is sucked with a straw from a soft plastic bottle the shape of the bottle can be influenced by the way you suck: suck gently and slowly and the cool drink flows out smoothly while the shape of the bottle stays basically the same. Suck hard and violently and the cool drink will flow faster but the shape of the bottle will start to contract and become distorted.

Roughly, the same reaction occurs in a Karoo groundwater aquifer when water is pumped from a borehole. When the pumping rate, or discharge rate as scientists call it, exceeds a certain limit, the area in the aquifer where the water is sucked from becomes slightly "distorted" or deformed near the borehole. Depending on the force of the discharge rate and the manner in which the borehole is pumped, this deformation could permanently destroy a Karoo borehole, leading to the well-known cry: "My borehole has dried up!" - which is often heard from people who depend on Karoo aquifers for their water supply.

According to Professor JF (Jopie) Botha, from the Institute for Groundwater Studies at the University of the Free State, groundwater aquifers in Karoo formations of South Africa are usually considered as unreliable sources of water, as illustrated by the difficulties experienced by towns such as Dealesville, Dewetsdorp and Philippolis with water supply schemes based on boreholes.

However, studies have shown that these aquifers must contain considerable volumes of water otherwise it will be difficult to explain the large quantities of water pumped daily from mines and buildings located in and on the formations respectively. One reason for this seeming discrepancy is that the behaviour of a stressed Karoo aquifer is determined by its very complex geometry, consisting of multi-porous rocks interspersed by a few bedding-parallel fractures. To neglect this geometry in the management and operation of these aquifers can damage the aquifer severely or even ruin it completely.

Botha says that there is sufficient reason to believe that the inability of previous investigators to take the internal geometry of Karoo aquifers into account must be regarded as the main reason for the difficulties experienced with these aquifers and why people distrust them.

"The real problem with these aquifers might thus be more a management problem than a shortage of water."

To study this problem Professor Botha and his team at the Institute for Groundwater Studies conducted a research project, funded by the Water Research Commission, into the flow and transport characteristics of groundwater in Karoo formations. The results of the investigation were new and far reaching and included an innovative three-dimensional poro-elastic model for determining groundwater flow through the Karoo aquifers. The main purpose with the model was to investigate to what extent deformations are responsible for the observed physical behaviour of Karoo aquifers in South Africa, which cannot be explained with the conventional porous flow model. This applies in particular to the effect that linear and nonlinear deformations may have on the behaviour of the aquifer.

BACKGROUND

A common view of the Karoo formations in the past was that the rocks are very tight and that the formations can only store water in vertical and sub-vertical fractures. However, Botha says their research shows that this is not the case.

"Vertical and sub-vertical fractures do occur quite frequently in these formations, but they only serve as preferential flow paths during the recharge of the aquifers and not as storage units. The major storage units of water in Karoo aquifers are the formations themselves. Because these formations are very tight, they do not transmit water readily, but the bedding-parallel fractures can serve as the conduits

Left:*A groundwater storage facility at Dealesville in the Free State – a small town with a water supply scheme based on boreholes.*
Right:*A sealed exploration borehole.*

and transmit water in these aquifers."

He says a borehole in a Karoo aquifer therefore only has a significant yield if it intersects one (or more, but usually one) bedding-parallel fracture. Although these fractures often extend over large areas, they can only store a limited volume of water, because of the size of their apertures, which are of the order of 10 mm. The apertures, nevertheless, are large enough to allow them to transmit water rapidly to any point in the aquifer where the fracture is present and there is a demand for water.

An American hydrologist, OE Meinzer already argued in 1928 that aquifers are compressible.

Nevertheless, the compressibility of an aquifer is habitually neglected in groundwater investigations, because the magnitudes of these phenomena are small and difficult to observe in practice. However, the magnitudes of the deformations are such that they could collapse a fracture with the aperture of a water-yielding fracture in the Karoo formations in a few decades or less, even though the deformation might not be recognized during normal field investigations of an aquifer.

MODEL

The project team concentrated their efforts on the development of a deformation model. This model showed that deformations might play a much larger role in the behaviour of aquifers in general, and not only Karoo aquifers, as was originally thought. This means that one should use a model that also takes the mechanical properties of the aquifer into account and not a model that only depends on the classical hydraulic parameters (specific storativity and hydraulic conductivity), when modelling the flow of groundwater in practice.

The deformation model was supplemented with a two-dimensional mass transport model to study mass transport in an aquifer subject to deformations. However, this showed that there is no significant difference between mass transport in a deformable and a rigid aquifer, provided that the discharge rate of a borehole is not so high as to cause oscillations in the water levels of the aquifer and the mass transport model becomes unstable.

Previous studies on the deformations of aquifers have usually been based on the generalized linear law of Hooke – one of the keystones of the theory of elasticity and the basic principle governing the operation of the classical spring balance (the more massive a body, the longer the extension of the spring). This law, unfortunately, does not allow one to study residual deformations, (the spring in the balance will not return to its original length, if used to weigh a body whose mass exceeds the maximum mass for which the balance was designed), which could be important in Karoo aquifers.

Since the linear law of Hooke cannot account for residual deformations, a new non-linear form of law was introduced to study residual deformations in aquifers.

Botha says there are no analytical solutions available for the coupled flow and momentum equations that arises from the application of both the linear and non-linear forms of Hooke's law to the flow of groundwater through deformable aquifers, at least not to the knowledge of the researchers. The finite element method was therefore used to approximate the equations and a computer program was developed for the numerical computations of solutions.

The computer program was first used to study a model for a hypothetical aquifer system – with the view to test and verify the present model. Thereafter the model was used to study the behaviour of the aquifer on the Campus Test Site of the University of the Free State.

TEST SITE

When the model was applied to the aquifer on the University's Campus Test Site with its bedding-parallel fracture, dramatic changes were observed. Although the simulated draw downs and displacements remained smooth for all simulations with the linear law of Hooke, the fracture experienced significant deformations if the discharge rate of the borehole exceeded a certain limit.

The same also applies in the case of the non-linear law of Hooke, except for the introduction of residual deformations with magnitudes that depend quadratically on the discharge rate of the borehole. The residual deformations ultimately led to a chaotic behaviour of both the simulated draw downs and displacements at high discharge rates.

The model thus clearly supports the view that too high discharge rates could damage a borehole and a Karoo aquifer permanently.

An interesting prediction by the model is that no deformations will form in the aquifer, even under the non-linear law of Hooke, if the discharge rate of the borehole is kept below a certain value. However, this behaviour is typical of all deformable bodies and there is no reason to expect that aquifers should behave otherwise.

Knowledge of this limiting discharge rate of boreholes obviously would enhance the management of aquifers considerably. Unfortunately, the limiting discharge rate depends intrinsically on the hydraulic and mechanical parameters of an aquifer which vary considerably from aquifer to aquifer. The parameter can therefore only be determined through detailed field investigations.

The non-linear law of Hooke caused constrictions to develop in the fracture immediately after the pump is switched on, if the discharge rate of the borehole exceeds the limiting rate. The magnitudes of the constrictions increase very quickly at first, but then approach a pseudo steady state within a few hours of pumping (two in the case of the model).

A series of simulations was performed to try to find to what extent the pumping of the borehole will affect the fracture in the model of the Campus site. According to the results of the simulations, a borehole on the Campus site will fail in less than six years, if pumped at a rate of 8.3 m^3 (cubic metres) per hour for 8 hours per day, every day of the year. However, the results also indicate that the fracture will suffer no significant mechanical damages if the discharge rate is kept at or below 1.4 m^3 per hour. The mechanical properties of a fractured aquifer are therefore as important as the hydraulic properties of the aquifer in designing a discharge rate for a production borehole in such an aquifer. More attention should therefore be paid to the mechanical properties of the aquifer in the management and control of well fields.

The fact that constrictions develop very quickly in the fracture at early times of pumping and then approach a pseudo state suggests that it would be more advantageous to pump a borehole for extended periods rather than intermittently. For example, pump the borehole once for 24 hours in a cycle of 72 hours rather than three times for eight hours each, as is usually done in water supply schemes. This procedure will increase the expected mechanical life of the borehole by a factor of 3 for a given discharge rate. Longer periods of pumping will increase this time proportionally.

A very important conclusion that can be drawn from this study is that a "dried-up" borehole does not imply that there is no longer water in the aquifer, but that the borehole has been damaged mechanically, in the sense that its ability to yield water has been destroyed, in most cases permanently. It is therefore often possible to drill a new successful borehole within a few metres from the damaged borehole. However, this practice should be discouraged by all means, because the new borehole will certainly also fail in future if pumped at too high a discharge rate. A repetition of the practice could therefore ruin the aquifer itself and not only a borehole. It is therefore of the utmost importance that the boreholes in water-supply schemes must be pumped at rates that will prevent mechanical damage to the borehole, to protect the aquifer for future generations.

For more information, readers can order a copy of the full report entitled "*Karoo Aquifers – deformations, hydraulic and mechanical properties*" (WRC Report 936/1/04). To order, please call Rina Winter or Judas Sindana at the Water Research Commission. Tel: 012 330 0340. Fax: 012 331 2565. E-mail: publications@wrc.org.za