Specific methods for the evaluation of hydraulic properties in fractured hard-rock aquifers

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Bloc underlined by fracture networks mainly compose hard-rock aquifers. The complexity of flows through fractures makes inadequate the use of classical techniques for the interpretation of hydraulic tests. Four different methods, well adapted to the complexity of groundwater flows in hard-rock aquifers, are presented for pumping well and/or observation well interpretations. The Neuman method is suited for unconfined anisotropic aquifers, while the Gringarten method is developed for the case of a single horizontal fracture. The Warren and Root method takes into consideration the heterogeneity of the medium, allowing the introduction of a double-porosity aquifer (transmissive fractures and capacitive matrix). Finally, the fourth method, Barker theory, assesses the flow dimension related to spatial distribution of conductive fractures and their connectivity. All these methods are presented and illustrated on pumping tests carried out in a granite terrain, south of Hyderabad, India.

LARGE tracts of South India are underlained by hard crystalline rock terrain (granite, gneiss, basalt, etc.). The area is also classified as semiarid to arid, generally prone to drought conditions, requiring optimal management of groundwater resources against increasing demands of water for various activities (agricultural, industrial and domestic). Estimating the hydraulic characters of water-bearing layers is an essential part of groundwater studies. The most effective way of determining these characteristics is to conduct and analyse *in situ* hydraulic tests. One of the early records of pumping tests on a large scale in India was done by Vincent and Sharma[1]. The study indicates that well losses comprise a significant portion of the total drawdown in a number of low- and high-yielding wells. Karanth and Prakash[2] observed that the transmissivity values (*T*) obtained by slug-tests are more than pump-test values for low *T* values, and that they vary from negligible up to a factor of about three for higher *T* values. Pradeep Raj *et al.*[3], from hydrological tests on dug wells in the crystalline rocks, estimated a range of *T* values from 26.5 to 56.36 m^2/d, for the weathered zone based on the interpretation made using the Papodopulos and Cooper method[4]. Ballukraya[5], from a study in Karnataka, postulates that the yield fluctuation in the pre- and post-monsoon periods is largely dependent on recharge that is restricted to about 60 m depth. All these studies considered hard-rock aquifer as isotropic and homogeneous, which is not the case as demonstrated below.

The fresh unaltered massive hard rock is not water-bearing, but the weathered zone and fissured and jointed zones are productive. In general, the weathered horizon, when water-saturated, is poorly transmissive with high storage while the fissured and jointed zones are poorly capacitive, but highly transmissive. The problem of flow through fractures or a fractured environment is primarily a problem of flow through a dual-porosity medium, which includes the porous matrix and the fractured network. These two components are hydraulically interconnected and cannot be treated separately. The degree of interconnection between these two media defines the character of the entire flow domain, and is a function of the hydraulic properties of each of them. These properties include matrix hydraulic conductivity and fracture-network distribution, orientation, apertures, connectivity and thus, bulk hydraulic conductivity. They will also determine the heterogeneity and anisotropy of the whole aquifer. The complexity of flows through fractures makes inadequate the use of classical techniques such as Theis and Jacob methods for the interpretation of hydraulic tests. Basically, in the hard-rock context, assumptions (homogeneity and isotropy) attached to such methods are not coherent with reality. Thus, there is need for alternative techniques for the evaluation of aquifer parameters able to involve the specificity of hard-rock aquifers.

Four different methods are presented below for the interpretation of pumping tests, well adapted to the complexity of groundwater flows in hard-rock aquifers. The method of Neuman[6] is suited for unconfined anisotropic aquifers, while Gringarten method[7] was developed for the case of a single (horizontal) fracture intersecting the pumping well. These methods are complementary, dealing both with anisotropy at the observation and pumping wells, respectively. The Warren and Root[8] method takes into consideration the heterogeneity of the medium, allowing the introduction of a double-porosity aquifer (transmissive fractures and capacitive matrix). Finally, the fourth method, Barker theory[9], opens the way for the assessment of flow dimension and degree of connectivity between the fractures. All these methods are incorporated and illustrated on observations obtained from pumping tests carried out in the same study area.

The Maheshwaram watershed located in the Ranga Reddy district, Andhra Pradesh, India is the main study area of the Indo-French Centre for Groundwater Research (French Geological Survey/National Geophysical Research Institute). This watershed, located 30 km away from Hyderabad, covers a surface of about 55 km^2, and is mainly constituted by Archean granites. The weathering profiles are observable through many dug-wells earlier

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used by the farmers for irrigation. Profiles are generally truncated by erosion: under a few decimetres of redsoil, while the alterites are thick with less than 5 m. A high density of horizontal fractures is observed in the fissured zone[10]. Vertical fractures with a tectonic origin are also present. Due to the overexploitation of groundwater resources, water levels are far below ground level and the alterites are dry, while only the fissured zone is saturated. This specificity was used to realize pumping tests with the objective to test the four interpretation methods mentioned above and thus to characterize the hydrodynamic properties of the fissured layer only.

For instance, on a bi-logarithmic plot (Figure 1), the drawdown curves at observation wells IFP-1/1 and IFP-1/2 during pumping tests at IFP-1 have a complex shape, difficult to interpret with classical methods (Theis, for example). Drawdown curves are composed of three parts: the first one, at short times with strong slopes is followed by an intermediate period during which water level stabilization occurs; a third part for long times shows a new increase in slopes.

The theory initially developed by Boulton[11] to interpret some special curves obtained in observation wells takes into account the notion of delayed yield from storage in unconfined aquifers[12]. It was improved by Neuman[6,13], who developed an analytical solution adapted to anisotropic unconfined aquifers, where K_r is the radial permeability parallel to the aquifer extension and K_z is the vertical permeability. The Neuman method considers an unconfined and infinite aquifer. When a constant discharge rate is pumped in a complete well, the water comes for one part from the storage in the aquifer and for the other part from gravitational drainage at the free surface. The Neuman solution, under abacus, gives reduced drawdowns in an observation well located at a radial distance r from the pumping well,

$$s_{DN} = \frac{4\pi Ts}{Q} \text{ as a function of:}$$

$$\text{reduced time } t_s = \frac{Tt}{Sr^2} \text{ for the } A \text{ curves and}$$

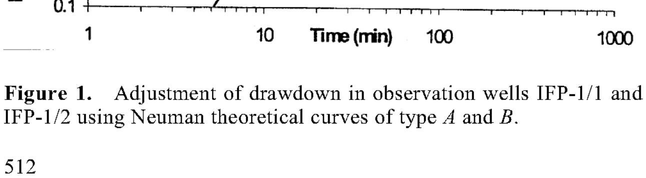

Figure 1. Adjustment of drawdown in observation wells IFP-1/1 and IFP-1/2 using Neuman theoretical curves of type *A* and *B*.

$$\text{reduced time } t_y = \frac{Tt}{S_y r^2} \text{ for the } B \text{ type curves,}$$

where T is the transmissivity of the aquifer, S the storage coefficient, S_y the specific yield, s the drawdown, t the time since the starting of pumping. The interpretation using this method consists in fitting the observed drawdowns on the abacus constituted by two types of curves: type A curves for short times and type B curves for late times. Both curves are characterized by the same parameter $\beta = \frac{r^2 K_D}{b^2}$, which is a function of the permeability anisotropy $K_D = \frac{K_z}{K_r}$, the thickness of the aquifer b and the distance r between the observation and pumping wells.

The application of this method (Table 1) to the observation wells IFP-1/1 and IFP-1/2 leads to the evaluation of transmissivities, storage coefficients (S) and specific yields (S_y). Similar values are obtained in each observation well for T_A and T_B, showing the coherence of interpretation of this pumping test using Neuman method. The values obtained for specific yields are consistent with those deduced both from indirect methods by magnetic resonance soundings[14] and from direct methods by adjustment of water-level fluctuations using a global model[15].

To determine K_D, the aquifer thickness b must be known. Flowmeter measurements during injection tests in eight wells of the basin have shown that the fresh basement does not contain any conductive fracture. This is the case in pumping well IFP-1. Thus, the top of this layer was chosen as the bottom of the aquifer. As for classical methods, the uncertainty on the value of r makes it difficult for interpretation of drawdown in pumping wells. The results of this interpretation (Table 2), show an anisotropy of the permeability tensor, in accordance with geological observations: horizontal permeability is systematically higher than the vertical one. This result is consistent with the observation of many horizontal fractures in dug-wells.

Flowmeter vertical profile in IFP-9 (ref. 10) shows that only one fracture is conductive (at 29 m depth) and is saturated during the whole pumping test. Moreover, analysis by Neuman method arises the existence of hydraulic anisotropy due to the existence of horizontal fractures[10]. Thus, the method developed by Gringarten and Ramey[16] for a vertical well intersecting a single horizontal fracture in an anisotropic aquifer (Figure 2), applicable to the pumping well, is well-adapted to the hydrogeological context of the IFP-9 well.

The complexity of the analytical solution necessitates an interpretation through the adjustment of observed drawdowns on theoretical curves of an abacus[7], giving the reduced drawdowns in a pumping well as a function of reduced time for various geometrical configurations represented by the parameter H_{DG}, when the fracture is located at the centre of the aquifer

Table 1. Transmissivity and storage parameters obtained by adjustment of drawdown. (T_A, Transmissivity obtained by adjustment on type A curve; T_B, Transmissivity obtained by adjustment on type B curve, T_{AB}, Average of T_A and T_B.)

Observation well	Pumping well	r(m)	T_A(m^2/s)	T_B(m^2/s)	T_A/T_B (–)	T_{AB} (m^2/s)	S (–)	S_y (–)
IFP-1/1	IFP-1	28	1.76E-05	1.96^E-05	0.90	1.86-05	7.0E-05	1.7E-03
IFP-1/2	IFP-1	27.5	1.71E-05	1.76^E-05	0.97	1.74E-05	3.7E-05	1.5E-03

Table 2. Permeability and anisotropy degree determined at observation wells using Neuman method

Observation well	β(–)	$r(m)$	$b(m)$	K_r(m/s)	K_Z(m/s)	K_D(–)	$1/K_D$(–)
IFP-1/1	1.00	28	21.8	8.5E-07	5.2E-07	0.606	1.7
IFP-1/2	0.20	27.5	21.8	8.0E-7	1.0E-07	0.126	8.0

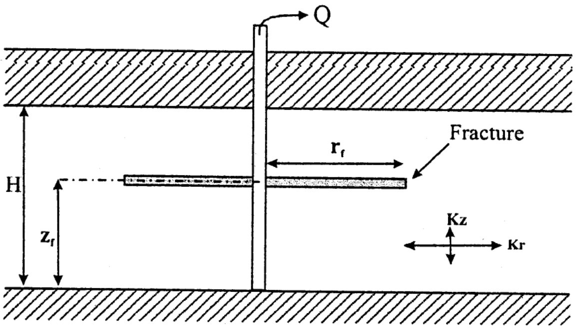

Figure 2. Schematic section of the Gringarten aquifer model (a single horizontal fracture).

$$\left(\frac{z_f}{H}=0.5\right), \text{ with } t_{DG}=\frac{K_r t}{S_s r_f^2},$$

$$s_{DG}=\frac{4\pi\sqrt{K_r K_z}\, r_f s}{Q} \text{ and } H_{DG}\,\frac{H}{r_f}\sqrt{\frac{K_r}{K_z}},$$

where z_f is the distance between the fracture and the bottom of the aquifer, H the aquifer thickness. K_r, the permeability along the radial direction parallel to the fracture, can be interpreted as the permeability increased by the existence of the horizontal fracture. K_z, the vertical permeability, represents the matrix permeability, S_s the specific storage coefficient, t the time since the pumping started, r_f the radius of the horizontal fracture, s the drawdown and Q the pumping discharge rate.

Adjustment of observed drawdowns by Gringarten theoretical curves (Figure 3) leads to high values of H_{DG}, suggesting a high permeability anisotropy. Difference between observations and theoretical curves at short times is attributed to well losses in the pumping well. Knowing the geometry of the case (i.e. the thickness H of the aquifer), assuming the distance z_f between the bottom of the aquifer and the fracture equal to 0.5*H and using the

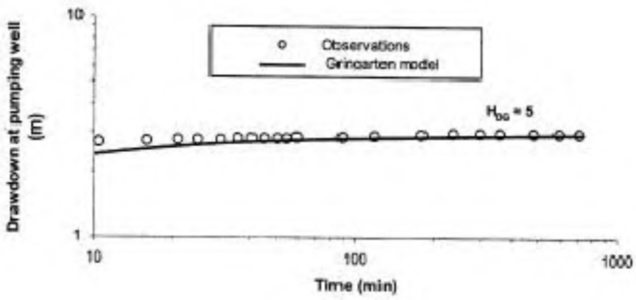

Figure 3. Adjustment of drawdown in pumping well IFP-9 using Gringarten theoretical curves.

value determined by Maréchal *et al.*[10] with Neuman method for S_S (9.7×10^{-5} at IFP-9), the hydrodynamic properties of the aquifer are evaluated (Table 3): K_r the horizontal permeability, K_z the vertical permeability and r_f radius of the horizontal fracture. It is observed that the anisotropy of the aquifer is shown in the pumping wells, while estimated fracture radius is coherent with field observations.

Due to the fact that blocs separated by fractures compose hard-rock aquifers, one method describing such behaviour has been proposed. This method derives from the conceptual double-porosity model developed by Barenblatt *et al.*[17]. The concept (Figure 4) supposes a confined aquifer constituted by two media: the fractures, transmissive but poorly capacitive, and the matrix, capacitive but poorly transmissive. Both mediums are characterized by hydraulic properties: K_f and S_f are the permeability and the storage coefficient of the fracture medium respectively, and K_m and S_m are the permeability and the storage coefficient of the matrix respectively. The flow radial to the pumping well is only controlled by the transmissivity of fractures (flow from matrix to pumping well is nil, $K_f \gg K_m$) and the fracture network drains the matrix where the flow is stationary (spatial variation of the hydraulic head is neglected). The expression of the drawdown is:

Table 3. Permeability, anisotropy degree and radius of horizontal fracture determined at pumping wells using Gringarten method. *S_S is the average of specific storage coefficient determined for each site using Neuman method at observation wells

Pumping well	Known parameters					Parameters determined by adjustment				
	H(m)	Fissure	z_f(m)	z_f/H (–)	S_S*(1/m)	H_{DG}(–)	r_f(m)	K_r(m/s)	K_z(m/s)	K_r/K_z(–)
IFP-9	7.3	F9/1	4.0	0.55	9.7E-05	5	3.4	2.9E-05	5.2E-06	5.5

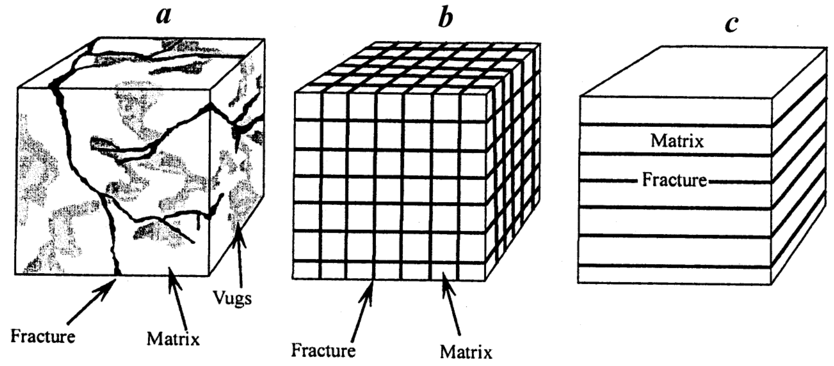

Figure 4. Double-porosity model. ***a***, Naturally fractured rock formation; ***b*** and ***c***, Warren and Root idealized fractured system. ***b***, Orthogonal fracture network (n = 3), and ***c***, Horizontal fracture network (n = 1).

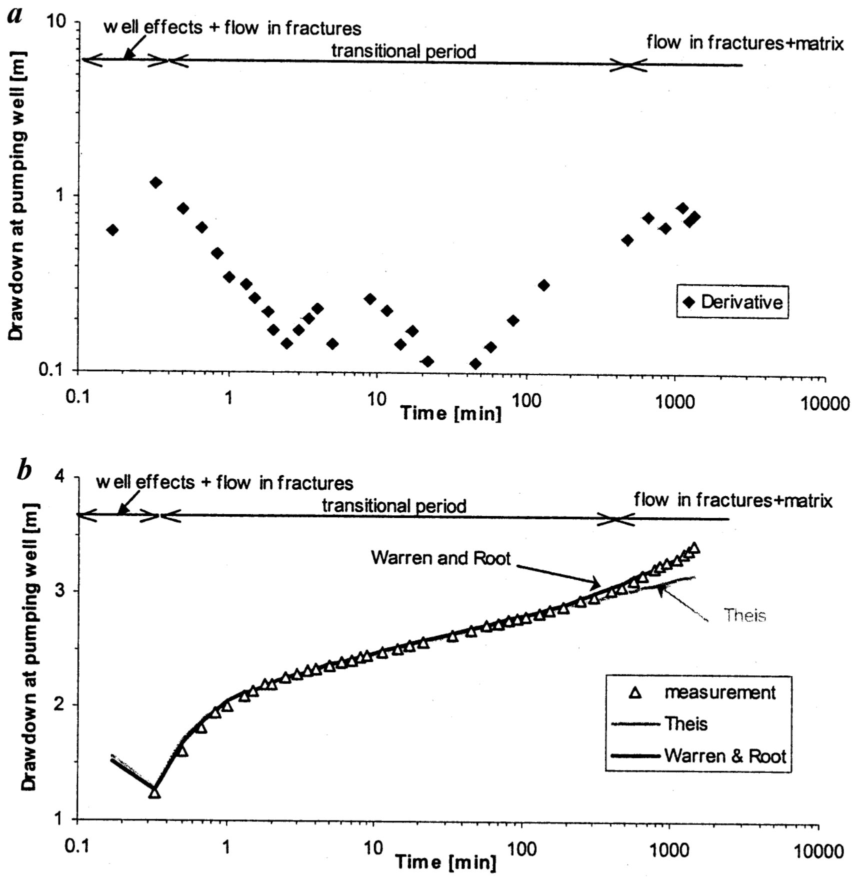

Figure 5. Interpretation at pumping well IFP-16 using a double-porosity model. ***a***, Logarithmic derivative at IFP-16, and ***b***, Adjustment of drawdown using Warren and Root (double-porosity) and Theis method.

$$s(r,\ t) = \frac{Q}{4\pi T_f} F(u^*,\ \lambda,\ \omega),$$

$$u^* = \frac{T_f t}{(S_f + \beta S_m) r^2}, \lambda = \alpha r^2 \frac{K_m}{K_f} \text{ and } \omega = \frac{S_f}{S_f + \beta S_m},$$

where λ is the interporosity flow coefficient (dimensionless), $\alpha = 4n(n + 2)/l^2$ is the shape factor, a parameter characteristic of the geometry of the fractures and aquifer matrix, where n (dimensionless) is the number of fracture sets (n = 1, 2, 3; see Figure 4), l the width of matrix blocs (in m), β a factor equal to 0 for early time analysis, equal to 1/3 for late time analysis (orthogonal system, n = 2, 3) or equal to 1 (n = 1), r a radial distance from the pumping well, T_f the fracture transmissivity ($T = HK_f$, H is the aquifer thickness), Q the pumping rate and t the time.

This method is well-illustrated at pumping well IFP-16. The logarithmic derivatives of drawdowns in IFP-16 have the typical shape of a double-porosity aquifer (Figure 5 *a*): (i) Well effects and flow trough fractures to pumping well, (ii) transitional period – the 'U' illustrates the contribution of the matrix flow through fractures to the pumping (note that in most cases, the 'U' of derivatives is often masked by well effects), and (iii) flow in fractures and the matrix. The application of Warren and Root method is then justified for this dataset (Figure 5 *b*). For the interpretation according to flowmeter measurements and geological observations, n = 3 and l = 1 m were used. The hydraulic conductivity of fracture network K_f = 5, 3 × 10^{-5} m/s and that of the matrix K_m = 7, 76 × 10^{-8} m/s. Figure 5 *b* also shows the interpretation using Theis method, which cannot properly interpret the drawdown after 470 min of pumping. This shows the limit of such models for hydraulic tests in hard-rock terrain, and consequently the necessity to use more sophisticated models.

In fractured aquifer, flow properties are controlled by the fracture distribution. The Barker model[9] takes into account the dimension of the flow, which results from the distribution and connectivity of the conductive fractures (Figure 6). This theory is a generalization of the Theis theory considering a radial flow, n-dimensional, into a homogeneous, confined and isotropic fractured medium characterized by a hydraulic conductivity K_f and specific storage S_{sf}. This generalized flow model introduces the fractional dimension of flow, n, which characterizes the variation law of flow section according to distance from the pumping well. Values of n vary from 0 to 3; the flow is spherical when n = 3 (Figure 6), cylindrical when n = 2

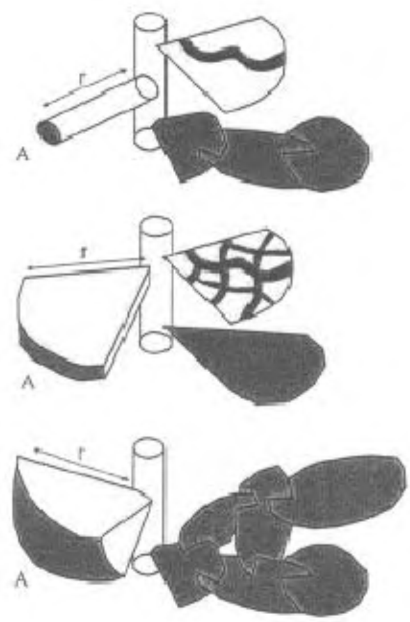

Figure 6. Concept of flow dimension (from ref. 18).

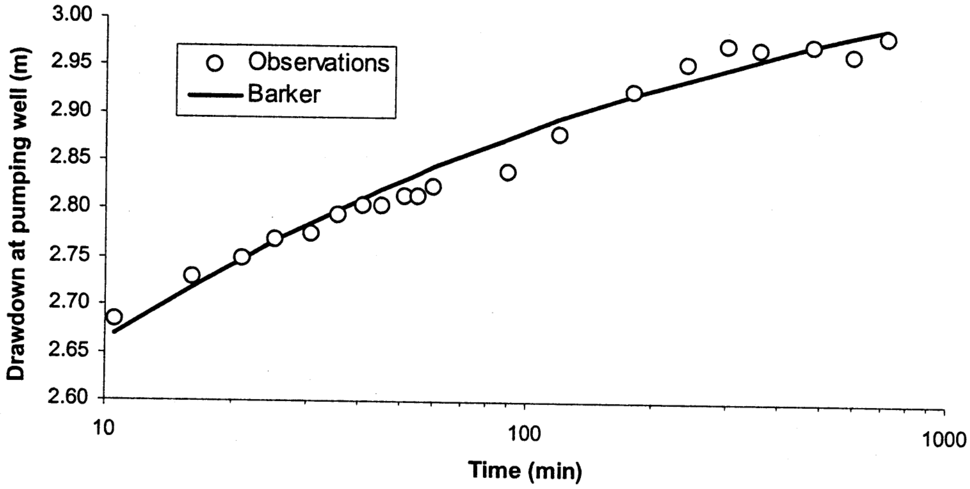

Figure 7. Adjustment of drawdown at pumping well IFP-9 using Barker theory.

(corresponds to Theis model) and linear when $n = 1$. Parameter n can take any value, entire or not, revealing the complex geometry of the flow. Expression of transient drawdown in the aquifer, $s(r, t)$, is given as follows.

$$s(r,t) = \frac{Qr^{2-n}}{4\pi^{n/2}K_f b^{3-n}}\Gamma\left(\frac{n}{2}-1,u\right), \qquad u = \frac{S_{sf}r^2}{4K_f t},$$

where $\Gamma(a,x) = \int_x^\infty e^{-t}t^{a-1}dt$ is the incomplete gamma function, r the radial distance from the pumping well, Q the pumping rate and t the time.

This method has been applied to pumping well IFP-9 (Figure 7). The generalized transmissivity $K_f b^{3-n}$ is evaluated: 1.66×10^{-4} $m^{1.5}/s$. The flow dimension is equal to 2.5 and thus corresponds to an intermediate flow between cylindrical (like Theis) and spherical. The flow seems to be generated by one sub-horizontal fracture network, or only a single horizontal fracture as suggested by flowmeter tests, connected to a second fracture network probably sub-vertical to vertical.

Aquifer tests in hard-rock terrain (granite, gneiss, basalt) make inadequate the use of classical techniques such as Theis or Jacob methods, and need specific methods taking into account the complexity of groundwater flow. The methods adopted in the present communication consider the heterogeneity and the anisotropy of the medium: anisotropy of permeability[6], single horizontal fracture intersecting the pumping well[7], double-porosity behaviour[8] or connectivity and fractional dimension flow[9]. These methods are successfully applied to case studies in Archean granites and allow to characterize the complexity of flows through fractures. These techniques should be widely used by scientists and engineers for fractured aquifer characterization (structure, anisotropy, heterogeneity) and evaluation (permeability, storage, water supply).

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