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A Numerical Study on the Relationship Between Transmissivity and Specific Capacity in Heterogeneous Aquifers

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Abstract

Specific capacity (Q/s) data are usually much more abundant than transmissivity (T) data. Theories which assume uniform transmissivity predict a nearly linear relationship between T and Q/s. However, linear dependence is seldom observed in field studies. Since hydrogeologic studies usually require T data, many hydrogeologists use linear regression analysis of T versus Q/s data to estimate T values where only Q/s data are available. In this paper we use numerical models to investigate the effects of aquifer heterogeneity on the relationship between Q/s and T estimates. The simulations of hydraulic tests in heterogeneous media show that estimates of T derived using Jacob's method tend to their late-time effective value much faster than Q/s values. The latter are found to be more dependent upon local transmissivities near the well. This explains why the regression parameters for T versus Q/s data depend on heterogeneity and the 'lateness' of the test period analyzed. Since this effect is more marked in high T zones than in low T zones, we conclude that natural aquifer heterogeneity can explain the convex deviation from linearity often observed in the field. A further result is that the geometric mean of T estimates, obtained from short and intermediate time pumping tests, seems to systematically underestimate effective T (T_{eff}) of heterogeneous aquifers. In the studied simulation cases, the median of the T values or the arithmetic mean yield better estimates for T_{eff}.

Introduction

Specific capacity (Q/s) of a well is defined as the ratio of discharge (Q) to drawdown (s) at the pumping well after a predefined period of pumping. It is the parameter most often provided by drillers to characterize the performance of a well, both because it is easy to measure and because well owners easily understand how much water they can get from the well. In contrast, estimation of transmissivity (T) requires more rigorous, longer-term testing, which is expensive. This explains why Q/s data are much more abundant than T data. Since T is the preferred parameter for many hydrogeologic purposes, it is common practice to estimate it from specific capacity data.

Most expressions relating T to Q/s are based on the Dupuit-Thiem equation or the Theis equation, which are analytical solutions of the two-dimensional flow equation for the most common radial flow boundary and initial conditions. The two-dimensional flow equation can be written in its general form as (Bear 1972)

$$\nabla(T\nabla h) + q = S(\partial h/\partial t) \quad \text{in } \Omega \qquad (1)$$

where h is head, T is the transmissivity tensor, S is storage coefficient, t is time, q is a sink or source term, and Ω is the problem domain.

Overviews of analytical expressions relating T to Q/s have been given by Banks (1992), Razack and Huntley (1991), and Huntley et al. (1992). An important example is the equation derived by Cooper and Jacob (1946) for the development of drawdown, s, in a well penetrating an infinite, homogeneous aquifer long after initiation of constant discharge, Q. The expression assumes radial flow, and when well losses are included, is given by

$$s = \frac{2.3Q}{4\pi T}\log\frac{2.25Tt}{S\,r_w^2} + CQ^n \qquad (2)$$

In this expression, T is the transmissivity, S is the storativity, t is elapsed time, r_w is the radius of the well, C is the well loss coefficient, and n is a constant greater than one (Todd 1980). Rearranging Equation 2 leads to the following expression for Q/s:

$$\frac{Q}{s} = \frac{1}{\frac{2.3}{4\pi T}\log\frac{2.25Tt}{S\,r_w^2} + CQ^{n-1}} \qquad (3)$$

Equation 3 indicates that Q/s decreases with t (and also with Q if well losses are present and if n > 2), the rate of decrease continually declining with time, although steady-state conditions are never attained because the aquifer is infinite. Nonetheless, if the change in Q/s with time is seen to become small, it is common to assume that steady-state conditions are approached, and that the Dupuit-Thiem equation can be used to estimate T from the inferred limit-

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Received February 1998, accepted February 1999.

ing Q/s value. Specifically, the relation predicts a linear relation between the two parameters given by

$$\frac{Q}{s} = \frac{2\pi T}{\ln \frac{R}{r_w}} \quad \text{or} \tag{4a}$$

$$T = A * \frac{Q}{s} \tag{4b}$$

The constant A depends on an assumed radius of influence (R) and frequently lies between 0.9 and 1.5 (Razack and Huntley 1991).

Most field observations indicate that T values predicted from Q/s data using the aforementioned analytical solutions do not agree well with T obtained from pumping tests. Therefore, many hydrogeologists try to find empirical relationships for different aquifers using linear regression analysis of T versus Q/s data (e.g., Delhomme [1974] for a confined eocene sand aquifer; Clifton and Neuman [1982] and Razack and Huntley [1991] for alluvial aquifers; Huntley et al. [1992], El-Naqa [1994], Sayed and Al-Ruwaih [1995], Fabbri [1997], and Mace [1997] for fractured and karst aquifers). Maps of T can be obtained by co-kriging limited T data with widely sampled Q/s data (Aboufirassi and Marino 1984; Ahmed and de Marsily 1987; Hughson et al. 1996).

The empirical relationships are usually derived from a first order linear regression using the logarithms of T and Q/s, because it is generally found that the logarithmic relationships display better correlations than the arithmetic ones (Razack and Huntley 1991), a result which is consistent with the widely held view that T is best approximated by a log-normal distribution (e.g., Gelhar 1993). Mace (1997) observed that T-Q/s data showed a convex deviation from linearity and thus obtained improved data fits using multiple linear regression with higher order polynomials (Figure 1).

Regression coefficients vary considerably depending on the case studied. Reasons for these variations are not completely clear. Razack and Huntley (1991) conjectured that turbulent well losses produced poor correlations between T estimates and Q/s data.

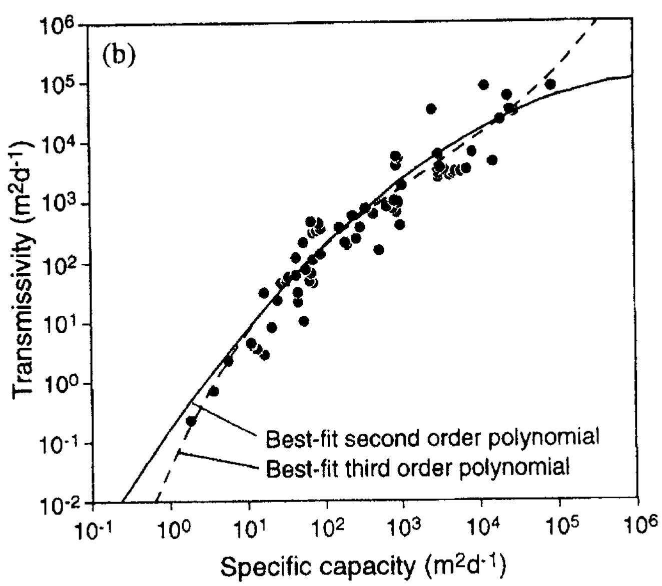

Figure 1. Typical relationship between transmissivity (T) and specific capacity (Q/s) for a karst aquifer (Figure 3b of Mace [1997]). Notice the convex (decreasing slope) nature of the T-Q/s dependence leading to better data fits using higher order polynomial linear regression.

Huntley et al. (1992) reported strong deviations from analytical expressions relating T and Q/s in a fractured rock aquifer, where turbulent well losses were believed to be less important. Mace (1997) attempted to take well losses explicitly into account by correcting Q/s using different approaches. He found that such corrections were associated with high uncertainties and could lead to well losses exceeding measured drawdowns. Mace (1997) compared regression parameters obtained from alluvial, fractured hard rock and karst aquifers, and proposed that the diversity of values could be attributed to the different types of aquifer heterogeneity.

The objective of this paper is to build upon Mace's work and evaluate the effects of natural aquifer heterogeneity on the relationship between T and Q/s using a numerical approach. A further objective is to explore the relationship between the effective T of heterogeneous aquifers and the different averages of T estimates from short and intermediate time pumping tests.

Numerical Simulations

The numerical simulation methodology consists of the following steps: (1) generation of hypothetical two-dimensional heterogeneous T fields; (2) simulation of single-well pumping tests at 169 locations in each T field using a finite-element code; (3) determination of Q/s and estimation of T (T_{est}) using Jacob's method (Cooper and Jacob 1946) applied to two time periods of the simulated drawdown curves; (4) plotting of Q/s versus T for the two time periods; and (5) comparison of the geometric mean, the arithmetic mean, and the median of the 169 T_{est} values with the effective T (T_{eff}) of each heterogeneous domain. This procedure is described more fully in the following paragraphs.

Four random T fields, square in shape and discretized into 500 by 500 square T zones of unit side length were simulated (Figure 2). The T values assigned to the zones are referred to as "point T values," and were generated using the computer code GCOSIM3D (Gómez-Hernández and Journel 1993). In this study, multiGaussian, nonmultiGaussian, and fractal T field distributions were investigated. The term multiGaussian means that any subset of point T values conforms to a jointly Gaussian distribution. This is by far the most widely used assumption in the geostatistical literature, but has never been shown to be realistic for natural aquifers, a fact which prompted inclusion of the other two T field types in the study. The multiGaussian T fields were generated using a spherical isotropic correlation function with integral scales (I) of 5 and 15 length units, arithmetic means for ln-T ($\langle Y \rangle$) equal to 0.0 (corresponding to geometric mean T of 1.0), and ln-T variances (σ_Y^2) equal to 1.0 or 4.0. The four multiGaussian T fields are denoted by MGT5-1, MGT5-4, MGT15-1, and MGT15-4, where for example MGT5-1 denotes a multiGaussian field with I = 5 and $\sigma_Y^2 = 1.0$.

The nonmultiGaussian T fields were generated by connecting high T values of an originally multiGaussian field, while maintaining the histogram for the ln-T field and the normality of the univariate distribution of T values. The variogram and the multiGaussian distribution of the original field were not retained. These fields were generated with $\langle Y \rangle = 0.0$ and σ_Y^2 values of 1.0 and 4.0 and are denoted by CONT-1 and CONT-4, respectively, to emphasize that high T values are better connected than low T values (Figure 2c).

The fractal T field, denoted FT, was generated having a power-law semivariogram $\gamma(h) = c\, h^{2\omega}$ with $\omega = 0.25$ and $c = 0.027$, as proposed by Neuman (1994). Further details on the generation of the T fields are given by Meier et al. (1998) who used similar T fields to evaluate Jacob's method for interpreting long term pumping

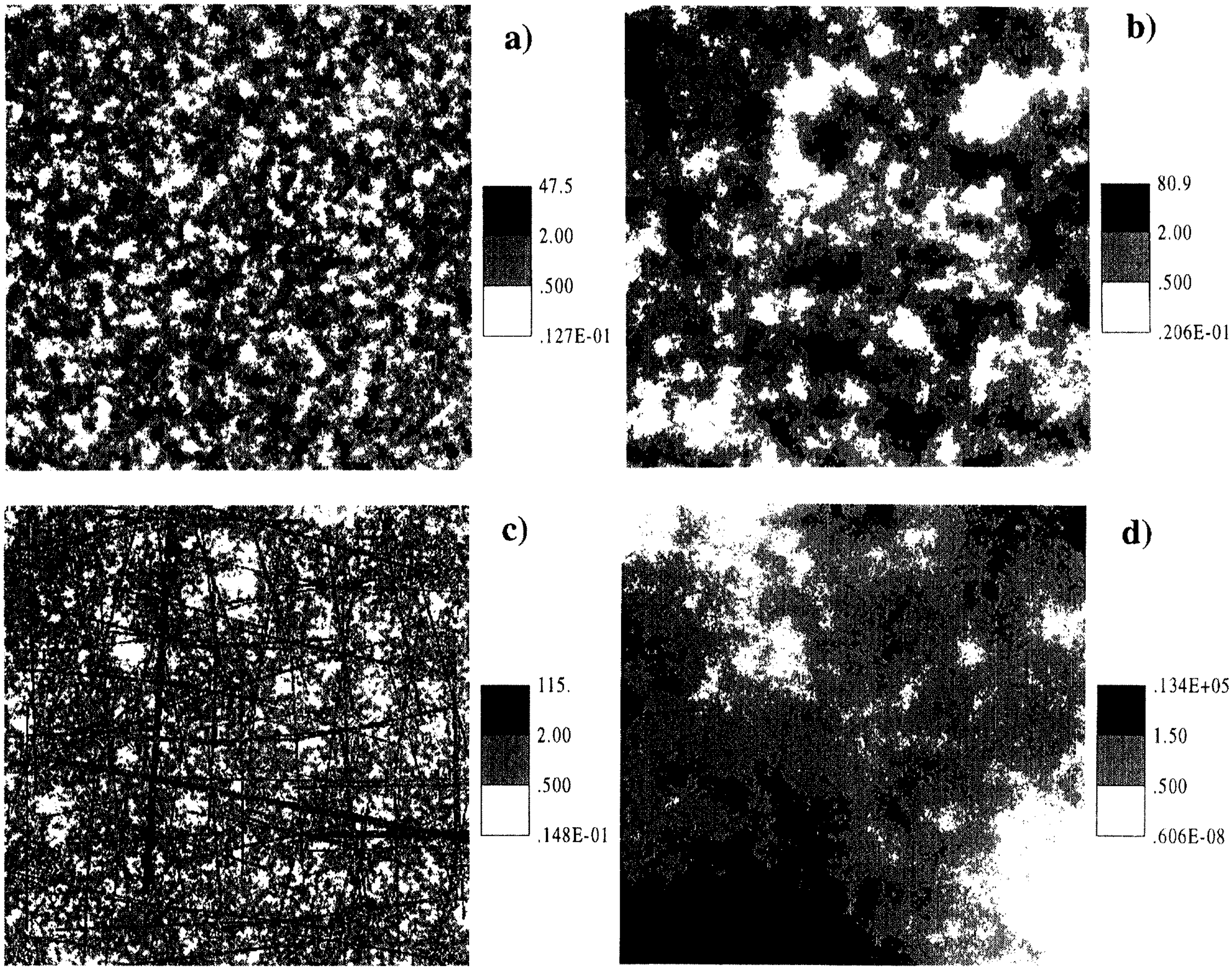

Figure 2. Random transmissivity (T) fields (side lengths of 500 units) used in numerical simulations. Black represents high T and white is low T. (a) and (b) multiGaussian T fields (NGT5-1 and MGT15-1) with ln-T variances (σ_Y^2) of 1.0 and integral scales of 5 (a) and 15 (b) length units. (c) NonmultiGaussian T field (CONT-1) with σ_Y^2 of 1.0. (d) Fractal T field (FT).

tests in heterogeneous formations. The procedure for generating the CONT fields is also described in detail by Sánchez-Vila et al. (1996). These authors suggest that the assumption of a multiGaussian distribution may not be valid in many field cases, even if point ln-T values display a Gaussian distribution. They also suggest that the appearance of scale effects in T may be attributed to deviation from a multiGaussian distribution.

A total of 169 pumping tests of intermediate duration were simulated in each of the heterogeneous T fields. The locations of the wells were chosen to describe a regular 13 by 13 grid with distances of 30 unit length in the x and y directions. Subdomains of 60 by 60 square T zones centered on each well were used in the flow calculations to limit CPU time (Figure 3a). In this way, almost the whole T field is covered by the pumping tests, while limiting the overlap of point T values such that only immediately adjacent pumping test zones shared common points. Each subdomain was enlarged on all sides by five lines of rectangular elements of increasing size to minimize boundary effects (Figure 3b). These additional elements were assigned a T value equal to the geometric mean of the whole 500 by 500 heterogeneous T field. Constant head conditions were applied to the boundaries of the enlarged subdomains. Within each subdomain, the finite-element mesh was strongly refined around the well, represented by a node, to improve numerical precision (Figure 3c). A homogeneous storativity (S) of 1.0 was used for all the simulations. This value was chosen to yield a geometric mean diffusivity (T/S) of 1.0 within the heterogeneous domain.

The transient flow equation (Equation 1) was solved with the finite-element computer code TRANSIN II (Medina et al. 1995). Special care was taken to ensure that the drawdown curves at the well locations were not significantly influenced by the homogeneous T zone surrounding the heterogeneous subdomain. Several preliminary simulations showed that this influence starts to be noticed at about 120 time units in subdomains with relatively high average T values. Thus, all simulations were terminated at 100 time units.

Following the approach of Beckie and Wang (1994), the radius of the well (r_w) required to evaluate the analytic expressions was determined as that which yielded the best match between numerically simulated drawdown curves obtained for the case of an homogeneous aquifer, and the curves predicted by the Theis (1935) solution for the same medium. Good agreement between the curves was obtained for a well radius of 0.0123 unit length. Note that r_w

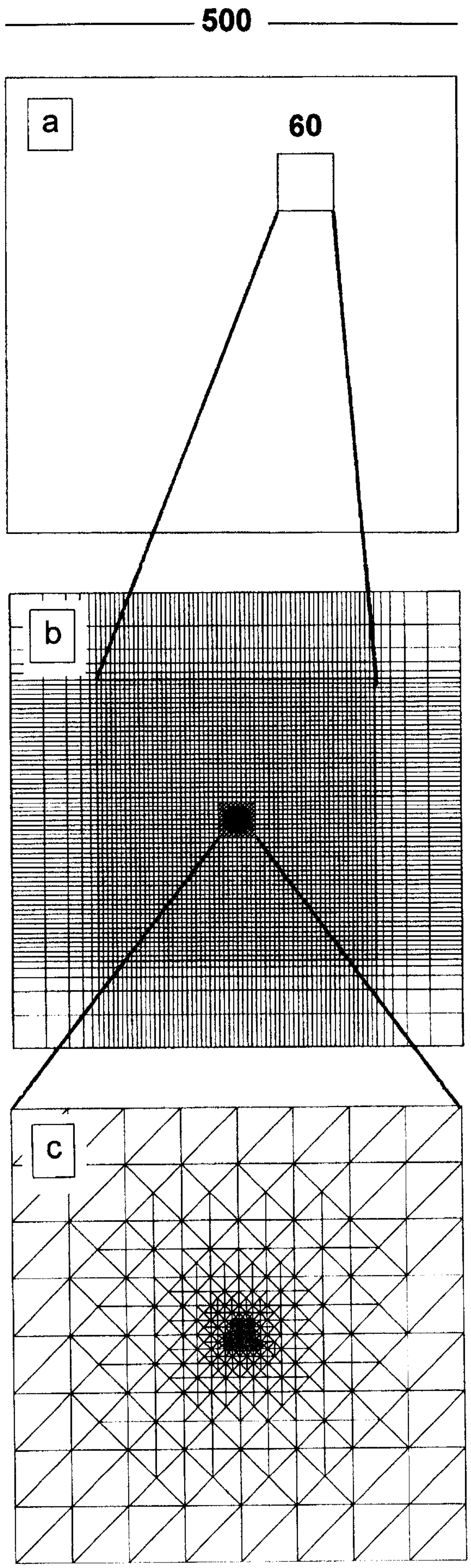

Figure 3. (a) Model domain (500 × 500) with one subdomain (60 × 60); (b) finite-element grid of subdomain with enlargement (five elements at each side; (c) refined finite-element mesh at the well.

is small in comparison to the integral scales of the investigated T fields.

Transmissivity (T_{est}) was estimated by applying Jacob's method to two different periods of the simulated drawdown curves: an early time period from 8 to 10 time units and an intermediate time period from 80 to 100 time units. The specific capacity (Q/s) was determined by dividing the flow rate by the drawdown at the end of each period. The T_{est} values are plotted versus the Q/s values for each time period and test case in Figures 4 and 5 together with the regression line (solid line). The relation predicted by the analytical nonequilibrium solution (Equation 3) was evaluated for a broad range of T; the corresponding analysis times, S = 1.0 and r_w = 0.0123. The predicted analytical relations are shown in Figures 4 and 5 as dashed lines for comparison purposes.

The linear regression parameters are listed in Table 1 for each time period, together with the geostatistical parameters and effective transmissivity (T_{eff}) values of the simulated T fields. T_{eff} is defined as the homogeneous transmissivity which yields the same flow rate as the heterogeneous T field in question using two prescribed head boundaries and two no-flow boundaries, resulting in parallel, steady-state flow through the entire model domain. The tabulated T_{eff} is the geometric average of the two T_{eff} values obtained by swapping the flow and no-flow boundaries. Since T_{eff} relates the mean head gradient to the mean flux (Gómez-Hernández and Gorelick 1989; Indelmann and Abramovich 1994; Neuman and Orr 1993), it is considered an appropriate quantity for comparison with the arithmetic and geometric averages and the median of T_{est} obtained from short and intermediate time pumping tests. It is important to mention that the analysis of late-time periods (at 20,000 time units) of long-term pumping tests using Jacob's method resulted in T_{est} values which were approximately equal to T_{eff} for the MGT and CONT fields (Meier et al. 1998).

Discussion of Results

The T-Q/s data points plotted in Figures 4 and 5 generally show a high degree of scatter, and the regression lines drawn through the populations have slopes and intercepts (Table 1) which in most cases differ significantly from those predicted by the analytical solution (Equation 3). Such deviations are qualitatively consistent with the observations of the field studies described earlier. The deviations are consistently greater and the regression coefficients consistently smaller for intermediate time (IT) than for early time (ET) evaluations. Specifically, the slopes of the regression lines are significantly smaller for IT than for ET in all simulated T fields, and all are smaller than the slope predicted from the analytical solution. Furthermore, the slopes and regression coefficients are smaller for CONT and MGT5 (small integral scale) than for FT and MGT15 (large integral scale). Data corresponding to low T and Q/s values tend to fall on the analytical solution, especially for ET. The ln-T variance (σ_Y^2) primarily affects the ranges of the T and Q/s values, but has only a slight effect on the shape of the relationship between T and Q/s. Since our numerical model differs from the analytical one only in the assumption of heterogeneity, we conclude that heterogeneity explains all the mentioned deviations from the analytical solution.

The relationship between the transmissivity in the immediate vicinity of the wells (T_w) and the Q/s and T_{est} values is shown in Figures 6a and 6b, and 6c and 6d, respectively, for the ET and IT simulations using the MGT5-1 T-field. The value of T_w for each well corresponds to the geometric average of the four T blocks of unit side length enclosing the well. The differences between the analytical

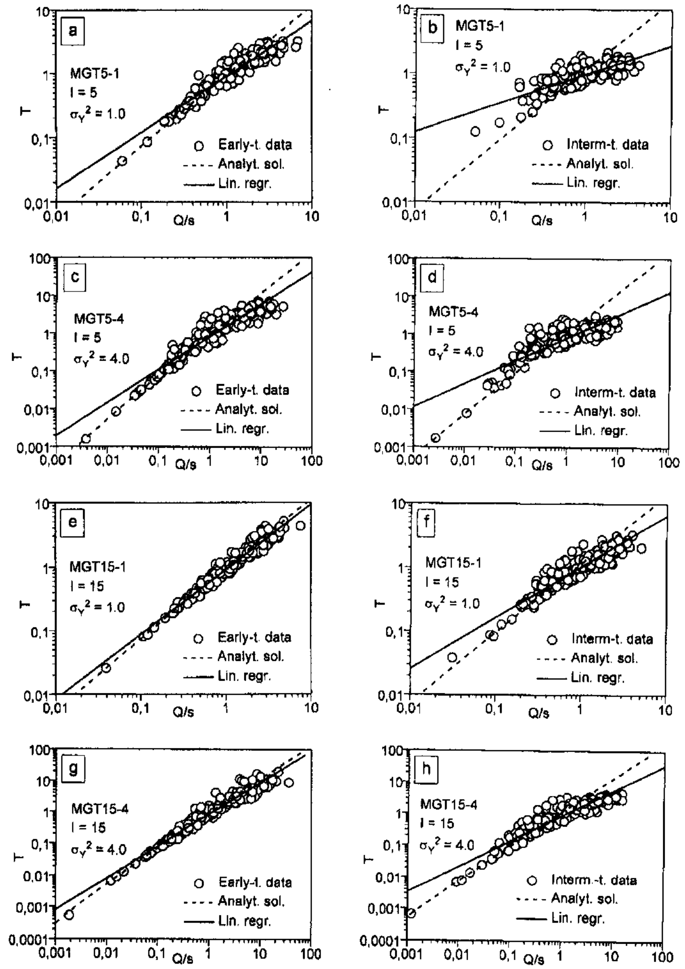

Figure 4. Log-log plot of T estimates versus Q/s from the early time and intermediate time analysis of the 169 pumping tests simulated in the MGT (multiGaussian T fields) with (a, b) $\sigma_Y^2 = 1.0$ and I = 5 length units; (c, d) $\sigma_Y^2 = 4.0$ and I = 5 length units; (e, f) $\sigma_Y^2 = 1.0$ and I = 15 length units; (g, h) $\sigma_Y^2 = 4.0$ and I = 15 length units. The linear regression line (solid line) deviates from the quasi-linear analytical solution (dashed line) for all cases.

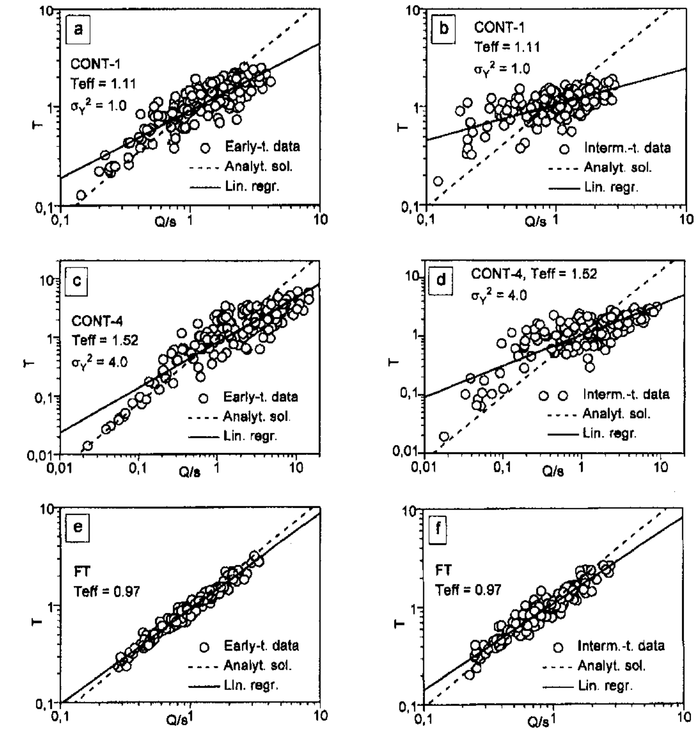

Figure 5. Log-log plot of T estimates versus Q/s for the early time and intermediate time analysis of the 169 pumping tests simulated in the CONT (nonmultiGaussian T fields) with (a, b) $\sigma_Y^2 = 1.0$; (c, d) $\sigma_Y^2 = 4.0$; and (e, f) in the FT (fractal T fields). The regression line (solid line) deviates from the analytical solution (dashed line) for all cases.

solutions (Equation 3) and the regression lines shown for T_w and Q/s (Figures 6a and 6b) are significantly smaller than for the relationship between T_{est} and Q/s (Figures 4a and 4b). The excellent correlation between Q/s and T_w demonstrates that Q/s is dominated by the transmissivity at the well. This numerical result is consistent with the field observations of Meier (1997), who found a good correlation between T_{est} from pulse tests and Q/s values from two-hour, constant rate pumping tests. In contrast, the corresponding T_{est} values are not dominated by T_w and moreover are sensitive to the test duration as indicated in Figures 6c and 6d. The 169 simulated pumping tests have the same duration, which is a realistic situation for most field testing campaigns. The radii of investigation of pumping tests in high T zones are much larger than in low T zones. This implies that T_{est} from pumping tests in high T zones represent areas larger than those of tests in low T zones. Therefore, T_{est} values from pumping tests in high T zones are closer to T_{eff} than T_{est} values obtained from low T zones. Furthermore, T_{est} at all locations tend toward T_{eff} with time, although at different rates.

The different behavior of T_{est} and Q/s in heterogeneous media explains both the scatter and the convex alignment of the T-Q/s data commonly found in field data (Figure 1). Specifically, convexity can be attributed to the fact that T_{est} tends to T_{eff} faster in high T zones than in low T zones. Consequently, the high T end of the T versus Q/s plots tends to flatten, leading to convex graphs. This effect is more marked for IT than for ET because the later the period used in analysis is, the closer T_{est} becomes to T_{eff}. This tendency of T_{est} to approach T_{eff} also explains the reduction in the slope of the regression line from ET to IT. In fact, this slope tends to zero as the pumping time increases because for very long times T_{est} tends to equal T_{eff}, as shown by Meier et al. (1998). This flattening is pronounced in the CONT simulations (Figures 5a through 5d), for which the connected high T zones control T_{eff}, and also in the MGT5 simulations, which have a small integral scale in comparison with the radii of influence of the pumping tests (Figures 4a through 4d). However, the T-Q/s data fall along a straight line for the fractal T field (Figures 5e and 5f) for which the integral distance tends to infinity (increases with the size of the domain). It is not clear whether this is due to the choice of parameters used for the T field generation or whether this is a general feature of fractal T fields, for which T_{eff} lacks any meaning.

The complexities associated with T_{est} also affect the averaging of the 169 T_{est} values. Table 1 indicates that the geometric mean of T_{est}, denoted T_{gest}, depends significantly on the test case and on the analysis period. After Matheron (1967), the geometric mean of point T values is generally considered to represent T_{eff}. However, the ratios $T_{gest}/T_{eff} \leq 1$ given in Table 1 suggest that T_{eff} may be systematically underestimated by geometrically averaging T_{est}. This must be taken into account when scale effects are studied using geometric mean values obtained from radial flow tests (e.g., Rovey and Cherkauer 1994; Schulze-Makuch and Cherkauer 1997). Furthermore, T_{gest} is consistently smaller for intermediate time data than for early time data. This might seem surprising, since the averaging area, defined by the ring of influence through which the front of the pressure

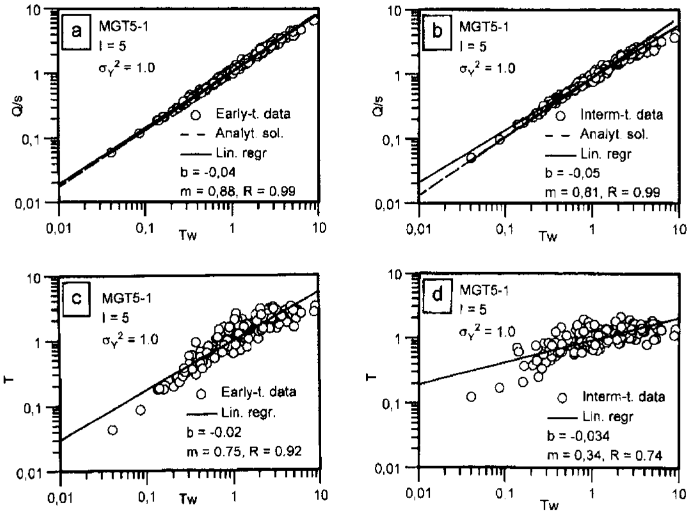

Figure 6: Transmissivity at the well (T_w) versus Q/s (a, b) and versus T estimates (c, d) for the early and the intermediate time analysis of the 169 pumping tests simulated in MGT5-1.

depression cone passes within the analysis period, is about 10 times larger for the intermediate time analysis than for early time analysis. Moreover, analysis of late time periods of long-term pumping tests using Jacob's method yields T_{eff} directly (Meier et al. 1998). Therefore, the evolution of T_{gest}/T_{eff} with test duration can be explained as follows. For very short test durations, T_{est} will be close to the point T values, so that T_{gest} will be close to the geometric mean of point T values, which is equal to T_{eff} for MGT. For very long pumping durations, T_{est} will tend to T_{eff} for all tests, so that $T_{gest} = T_{eff}$. During intermediate periods, T_{est} will tend to be close to T_{eff} in high T zones and to the point T value in low T zones, which leads to T_{gest}/T_{eff} values of less than one.

For most simulations, the median values, and in some cases the arithmetic mean values of T_{est}, are closer to T_{eff} than the geometric mean (Table 1). This is a consequence of high T_{est} values being closer to T_{eff} than low T_{est} values, as already noted, and of geometrical averaging giving greater weight to small values than do the arithmetic mean and the median value averaging. It may be worth mentioning that the use of rank statistics, such as the median, is often a robust practice in stochastic modeling (Gómez-Hernández and Carrera 1994). The method can overcome the problem of accounting for data values that lie below the measurement threshold (Guimerà et al. 1995), an advantage which is particularly important in low permeability formations.

Conclusions and Recommendations

1. The numerical simulations show that heterogeneity can explain the deviations from analytical expressions relating T and Q/s observed in real aquifers. Furthermore, heterogeneity influences the parameters obtained from linear regression analyses of T versus Q/s data.

2. In heterogeneous media, the slopes, the intercepts and the regression coefficients obtained from linear regression analyses of T versus Q/s data can depend considerably on the analyzed time period. The slopes and the regression coefficients are smaller and the intercepts are larger for late time than for early time data. Therefore, an empirical relationship derived from field data may only be useful for a certain time period. Moreover, such relationships are also sensitive to the type of heterogeneity.

3. The numerical simulations show that Q/s is dominated by T near the well. This is in conceptual agreement with the discussion of Butler (1990). Therefore, attention must be paid to the impacts

Table 1
Geostatistical Parameters of Simulated T Fields, Results from Linear Regression Analyses and Sample Means of T_{est} and Q/s Values

Geostatistical Parameters of Simulated T Fields					Linear Regression Analysis				Sample Means of T_{est} and Q/s					
Case	I	σ_Y^2	T_g	T_{eff}	Period	m	b	R	T_{gest}/T_{eff}	T_{aest}/T_{eff}	T_{mest}/T_{eff}	(Q/s)g	(Q/s)a	(Q/s)m
MGT5-1	5	1.0	1.02	1.02	ET	0.87	–0.049	0.94	**1.00**	1.27	1.17	1.17	1.58	1.20
					IT	0.45	–0.012	0.80	0.93	**1.00**	0.99	0.95	1.22	0.97
MGT5-4	5	4.0	1.02	1.02	ET	0.87	–0.103	0.94	**0.96**	1.86	1.48	1.28	3.33	1.42
					IT	0.61	–0.093	0.85	0.76	1.06	**0.99**	0.95	2.03	1.15
MGT15-1	15	1.0	1.00	1.00	ET	1.02	–0.044	0.98	0.94	1.31	**0.98**	1.04	1.44	1.05
					IT	0.80	0.008	0.93	0.90	1.12	**0.92**	0.86	1.17	0.88
MGT15-4	15	4.0	1.00	1.00	ET	1.01	–0.072	0.98	0.87	2.55	**1.00**	1.03	3.13	1.04
					IT	0.80	–0.070	0.93	0.72	1.32	**0.85**	0.82	2.22	0.90
CONT-1	–	1.0	1.00	1.11	ET	0.68	–0.044	0.86	0.91	1.04	**1.01**	1.18	1.46	1.25
					IT	0.36	0.022	0.65	0.93	**0.99**	**0.99**	0.96	1.14	1.05
CONT-4	–	4.0	1.00	1.52	ET	0.77	–0.097	0.89	0.69	1.09	**0.93**	1.43	2.86	1.85
					IT	0.53	0.022	0.79	0.73	**0.92**	0.88	1.09	1.95	1.32
FT	–	–	0.97	0.97	ET	0.98	–0.041	0.98	0.89	**0.99**	0.88	1.01	1.08	0.93
					IT	0.87	0.025	0.94	0.89	**0.99**	0.90	0.79	0.90	0.78

MGT: MultiGaussian T field
CONT: NonmultiGaussian highly connected T field
FT: Fractal field
I: Integral scale
σ_Y^2: ln(T)-variance
T_g: Geometric mean T of point T values
T_{eff}: Effective transmissivity

ET: Early time data analysis
IT: Intermediate time data analysis
m: Slope of regression line
b: Intercept
R: Regression coefficient

T_{est}: T estimates from pumping test analysis
T_{gest}/T_{eff}: Ratio between geometric average of T_{est} and T_{eff}
T_{aest}/T_{eff}: Ratio between arithmetic average of T_{est} and T_{eff}
T_{mest}/T_{eff}f: Ratio between the median of T_{est} and T_{eff}
(Ratios closest to 1.00 are given in bold)
(Q/s)a: Artimetic average of Q/s
(Q/s)g: Geometric average of Q/s
(Q/s)m: Median of Q/s

of artificial alterations of near-well T (e.g., skin effects). A recent overview of artificial alterations of near-well T is given by Butler and Healy (1998). Furthermore, turbulent well losses can exert an impact on Q/s data. Approaches for correcting Q/s data for head losses are discussed by Bradbury and Rothschild (1985) and Mace (1997). Skin effects and/or turbulent head losses will increase the deviations from the standard analytical expressions relating T and Q/s. However, these effects are not time dependent. Therefore, they do not affect the validity of the second conclusion.

4. Analyses with Jacob's method of short and intermediate time pumping tests performed in high T zones yield T_{est} values which are closer to T_{eff} than analyses of comparable time periods of pumping tests in low T zones. This behavior can play an important role when calculating sample means of T_{est}. The geometric mean of T_{est} from short or intermediate time tests can systematically underestimate T_{eff}. This fact should be considered when scale effects are studied using the geometric mean of values obtained from radial flow tests. In this work, the median and in some cases, the arithmetic mean values are closer to T_{eff}.

5. A conventional constant rate pumping test provides ground water modelers with a point T estimate at the well using Q/s and an average T for the ring of influence corresponding to the time period analyzed with the Jacob's method. Meier et al. (1998) show that this average T will approach T_{eff} for late time analysis periods.

Acknowledgments

The first author acknowledges financial support by SATW (Swiss Academy of Engineering Sciences). The work by the other authors was funded by ENRESA (Spanish Nuclear Waste Management Company), 1995SGR00405 (CIRIT) and AMB95-0407 (CICYT). The authors would also like to acknowledge constructive comments by J. Ward, K. Evans, and two anonymous reviewers.

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