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Constraining uncertainty of groundwater flow and transport models using pumping tests

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Abstract This paper demonstrates that characterization of sedimentary heterogeneity combined with the results from well-designed pumping tests is a powerful tool to develop realistic models for solute transport in a heterogeneous aquifer. For both a deterministic sedimentological facies model and the Gaussian geostatistical model, it is demonstrated how the early time portion of relatively inexpensive pumping test data can be used to predict solute transport. The pumping test data reveal connected high conductivity inter-well pathways, which dominate the solute transport in this aquifer. The models presented are inspired by data collected at the Columbus 1-ha test-site where a combined program of pumping tests and tracer tests was conducted to assess flow in a heterogeneous aquifer. Without any calibration attempt, the response of both the sedimentological facies model and the Gaussian geostatistical model shows characteristics of heterogeneous flow very similar to the field response. This indicates that both models capture essential elements to describe flow in the heterogeneous aquifer. It also implies that the sedimentological model combined with data from well-designed pumping tests can be used to define the basic impact of heterogeneity on transport behaviour, and that uncertainty of the geostatistical model can be constrained using the same pumping test data.

INTRODUCTION

Sedimentary heterogeneity can dramatically influence groundwater flow patterns and thus contaminant movement in sandy aquifers. Practising hydrogeologists are faced with a dual challenge: First, to grasp the range of possible aquifer responses and second, to make a reliable prediction of future aquifer response. Sedimentary aquifer heterogeneity plays a major role determining uncertainty. A reliable model prediction must include that uncertainty, and field measurements should be used to constrain that uncertainty (Deutsch, 1992). This article will show realistic examples of how aquifer heterogeneity can be assessed using basic sedimentological insight, and how uncertainty can be assessed using this insight. First, a sedimentological facies model is constructed consisting of major geometrical elements of heterogeneity for which plausible hydraulic conductivity values are assumed. Second, a Gaussian geostatistical model is constructed to screen the response of multiple possible conductivity fields representing the aquifer. For both cases a pumping test and tracer tests are modelled. It will be shown that the pumping test data can be quantitatively used to characterize the tracer transport between wells, i.e. to characterize connectivity between wells. Thus, it will be shown that a relatively inexpensive pumping test can be used to constrain uncertainty of solute transport. This work is a direct extension of field experiments including pumping tests and tracer transport conducted at the Columbus 1-ha test-site (Herweijer & Young, 1991). This experimental work provides a field confirmation for the proposed uncertainty and connectivity characterization method.

FIELD EXPERIMENTS AT THE COLUMBUS TEST-SITE

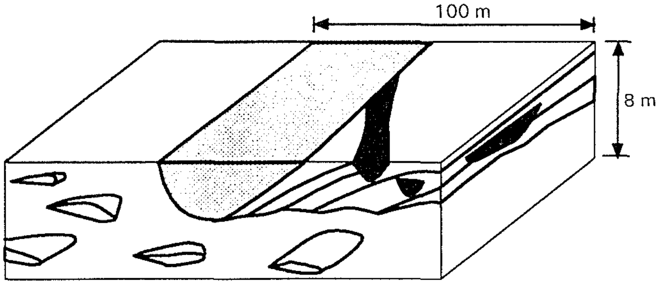
The Columbus test-site (Mississippi, USA) has been extensively used for field investigations of flow in heterogeneous aquifers (Boggs *et al.*, 1992; Young, 1995). The Columbus aquifer consists of approximately 10 meters of fluvial deposits. On a 1-ha test-site, 37 fully screened wells were installed. For all wells borehole flowmeter surveys were conducted and vertical profiles of hydraulic conductivity were determined. The measurements indicate that the aquifer is highly heterogeneous. Within single wells, hydraulic conductivity contrasts of a factor of 1000 were observed for layers with a thickness ranging from 0.5 to 1 m. Between wells, these high hydraulic conductivity layers could only be partially correlated. Thus, the aquifer consists of discontinuous high hydraulic conductivity lenses.

A suite of pumping tests and tracer tests was conducted at a test-site where a detailed network of 37 wells was drilled on a rectangular 1-ha plot (Young, 1991). The results of analyzing the pumping tests cover a wide range of values for aquifer parameters. Herweijer & Young (1991) show that the variability of early time drawdown, indicated by the variability of the interpreted storage coefficient, is a reflection of aquifer heterogeneity that is not (and can not be) accounted for in a conventional interpretation using type-curve models. From the combination of the pumping test results with breakthrough observed from small-scale tracer tests, Herweijer & Young (1991) conclude that the relatively low storage coefficients resulting from the conventional interpretation (i.e. a heterogeneous early time response ahead of the average response), are linked to highly conductive connections between pumping and observation well.

A large scale re-circulating tracer test was conducted. The four corner wells of the rectangular 1-ha well network were pumped at equal rates, and tracer was injected in the central well. Young (1995) compares the field-observed breakthrough pattern with the results from a homogeneous model calculation. The effect of heterogeneity becomes obvious from preferential transport, reflected by large differences for arrival times for wells at a similar distance from the injection point. For example, breakthrough time ranges from 9 to 60 days for wells at a radial distance of approximately 30 m from the central well and from 50 to more than 165 days for the corner wells at 75 m.

HETEROGENEITY AT THE COLUMBUS 1-HA TEST-SITE

Two different approaches were followed to obtain a model that, to a certain degree, realistically captures the aquifer heterogeneity. A sedimentological facies model was constructed (Herweijer & Young, 1991). This model is based on the surficial evidence of a buried meandering channel (mapped from an aerial photograph), and correlations



facies or architectural element	log-K measured min ... med ... max	model
1 main meandering channel deposits	1 -5.0 ... -2.9 ... -0.5	-3.0
2 pointbar deposits	2 -5.6 ... -3.4 ... -1.3	-4.0
chute (cross-pointbar) channel deposits	no field observations	-2.0
4 braided stream deposits	4 -6.7 ... -3.6 ... -1.8	-4.0

Fig. 1 Sedimentological model for the Columbus 1-ha test-site.

along profiles of borehole flowmeter logs for the subsurface extent of the buried channel. The channel width (about 70 m) and depth (about 5 m) fits well with an empirical width-thickness relation published by Leeder (1973). The channel is flanked by finer (less conductive) pointbar deposits. Borehole flowmeter logs indicate that streaks of high hydraulic conductivity (coarse material) occur outside the channel. These streaks are explained, using a model published by McGowen & Garner (1971), as chute channels branching over the channel banks during high flood stage. Possible dimensions for these chutes are within the following ranges: depth 0.5 to 1.5 m; width 3 to 8 m; length 10 to 150 m.. The channel-pointbar complex overlies about 5 meters of undifferentiated heterogeneous coarse deposits. These deposits are interpreted (Muto & Gunn, 1986) as braided river deposits, and are sedimentologically similar to the Mississippi deposits. Figure 1 presents a schematic model on the scale of 1-ha test-site.

Alternative heterogeneity information was obtained by geostatistical analysis of the extensive set of about 500 hydraulic conductivity measurements made using a borehole flowmeter. Young *et al.* (1991) and Rehfeldt *et al.* (1992) present a variogram analysis. The resulting variogram parameters, however, are subject to debate, and it appears that it is impossible to assign unique variogram parameters.

PUMPING TEST AND TRACER TEST RESPONSE FOR A SEDIMENTOLOGICAL FACIES MODEL OF THE COLUMBUS 1-HA TEST-SITE

Based on the geological and hydrological data available, one is faced with the question of how to assess uncertainty of flow and transport given that the sedimentological model of Fig. 1 bears some "truth", but the exact position of wells with respect to the location of the elements of the model that govern the hydraulic conductivity contrasts is

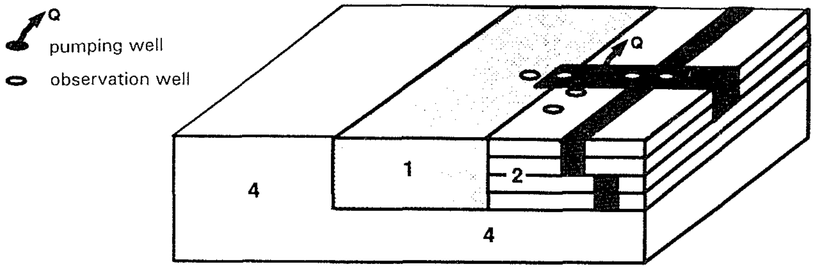


Fig. 2 Schematic sedimentological facies model (see Fig. 1 for legend).

unknown. The next section will address this problem using a fixed sedimentological model with a superimposed variable lay-out of wells that represent a flow system.

Figure 2 shows a schematic model that represents the sedimentological heterogeneity model discussed before (see also Fig. 1). Table 1 shows hydraulic conductivities for this model. The horizontal conductivities are inferred from borehole flowmeter conductivities measured at the Columbus 1-ha test-site. The facies sub-division was obtained using the available geological information (aerial-photo and correlations of borehole flowmeter logs) and is somewhat speculative (Herweijer, 1996). Relatively low vertical hydraulic conductivities were assumed for the facies that are cyclical deposits; therefore these facies may contain thin fine layers (pointbar and chute channel fill). A moderate K_h/K_v ratio of 3 was assumed for sediments without fine cycles.

A pumping test was modelled using the well lay-out shown in Figs 2 and 3. Similar to the tests conducted at the Columbus 1-ha test-site, the central well located close to the buried channel is pumped. It is assumed that the central well is positioned in a highly conductive chute-channel at a small distance of the main fluvial channel. Wells 1 to 8 are observation wells (all at radial distance R = 30 m). Figure 4 shows the modelled pumping test response. The early time response shows a large variation. Observation well 1, which is positioned in the highly conductive chute channel, shows the first response. Observation wells 4 and 5, which are positioned in the medium conductive main channel, follow in response. The latest response is shown by observation wells 2 and 3, which are positioned on the low conductive point bar. For a certain (early) time,

Table 1 Conductivities used in the facies model.

Facies	Horizontal conductivity K_h:		Vertical conductivity K_v:		K_h/K_v
	log	m s^{-1}	log	m s^{-1}	
Channel	−3.0	1.0×10^{-3}	−3.5	3.3×10^{-4}	3
Pointbar	−4.0	1.0×10^{-4}	−5.5	3.3×10^{-6}	30
Chute channel	−2.0	1.0×10^{-2}	−3.5	3.3×10^{-4}	30
Braided	−4.0	1.0×10^{-4}	−4.5	3.3×10^{-5}	3

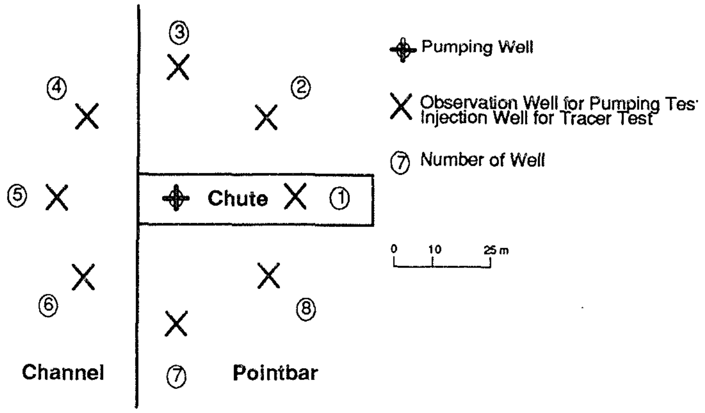


Fig. 3 Lay-out of pumping test and two-well tracer test model relative to the schematic sedimentological facies model (also see Fig. 2).

the level of drawdown varies over nearly two log cycles (by a factor of 100). A certain level of drawdown is reached for a time that varies over nearly two log cycles.

Using a node-node routing particle tracking technique (Desbarats, 1990, 1991; Goode & Shapiro 1991), a two-well tracer test was modelled between each individual observation well and the pumping well. Tracer flow was modelled dispersion free, i.e. only numerical dispersion occurs (due to the finite length grid). Figure 5 shows the tracer breakthrough. Peak breakthrough time ranges between 3 and 100 days, depending on the conductivity heterogeneity between the central injection well and the different observation wells. A good correlation exists (see also Herweijer, 1996) between the time of 5% cumulative tracer breakthrough (approximately peak breakthrough) and the time of head breakthrough (the time that drawdown exceeds a given threshold set at 0.001 m). Thus, the highly conductive chute channel that causes rapid transport of tracer is also responsible for preferential expansion (diffusion) of the drawdown cone.

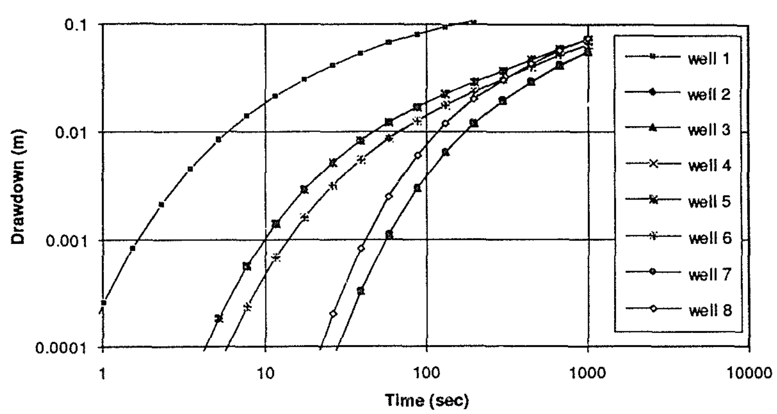


Fig. 4 Drawdown response for eight observation wells on a circle at $R = 30$ m.

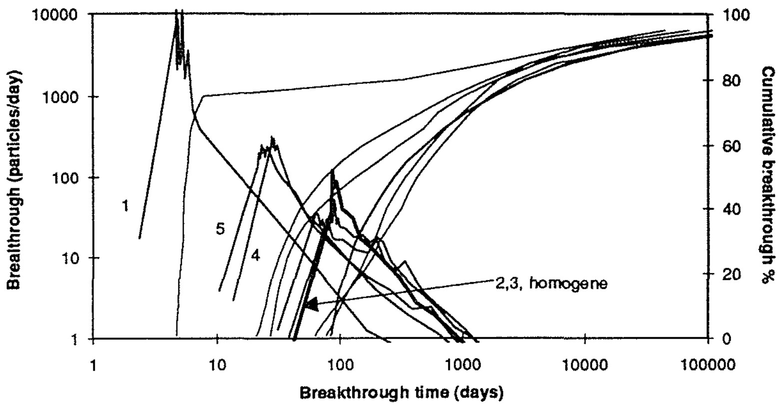


Fig. 5 Cumulative tracer breakthrough for five two-well tests in facies model (numbers indicate wells where tracer is injected).

PUMPING TEST AND TRACER TEST RESPONSE FOR A GAUSSIAN GEOSTATISTICAL MODELS REPRESENTING THE COLUMBUS 1-HA TEST-SITE

As discussed earlier, unambiguous determination of a variogram poses serious problems, even if a wealth of field measurements is available. Therefore a "reasonable" variation of variogram model parameters was chosen across the spectrum defined by field determined variogram parameters (Young, 1991) and above presented dimensional information from geological analogues. Table 2 presents the three-dimensional variogram parameters of a Gaussian model for four different "Variogram" options. Option 1 and 2 are anisotropic, and options 3 and 4 are isotropic. The maximum range varies from 5 to 25 m.

Honouring the three-dimensional variogram presented in Table 2, stochastic simulations were conducted conditioned to a fixed conductivity profile of the central well. For each variogram option four realizations were created. In total 16 stochastic conductivity fields (3D-cubes) were created for a grid of 112 by 112 cells and 6 layers. Figure 6 shows two examples of a conductivity layer for realizations of variogram option 1 and 4, respectively.

Table 2 Variogram parameters for "variogram" options of Gaussian model 16 Gaussian stochastic conductivity fields with different variogram parameters.

"Variogram" option	Horizontal range (m):		Vertical range (m)	Stochastic conductivity field
	North-south	East-west		
option 1	25	5	1.6	1-4
option 2	10	5	1.6	5-8
option 3	10	10	1.6	9-12
option 4	5	5	1.6	13-16

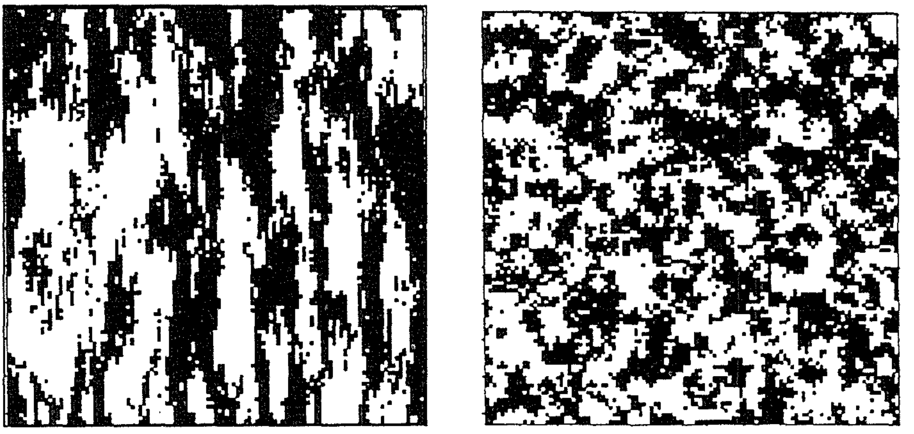


Fig. 6 Gaussian hydraulic conductivity models. The black area represents the 30% highest conductivity values. Variogram option 1 and 4, stochastic conductivity field 1 (*left*) and 13 (*right*).

Similar as described for the sedimentological model a pumping test was modelled using the well lay-out shown in Fig. 3. The central well is pumped while wells 1 to 8 are observation wells at radial distance R = 30 m. Figure 7 shows the drawdown response for the two stochastic conductivity fields in Fig. 6 (for all eight wells at radial distance R = 30 m). The response of the Gaussian stochastic conductivity fields shows a significant variability. The drawdown response of stochastic conductivity field 1 (representing the strongest and most anisotropic heterogeneity) shows the largest early-time variability and resembles the drawdown response of the sedimentological facies model. The drawdown response of stochastic conductivity field 13 (representing relatively weak and isotropic heterogeneity) shows a relatively small variability.

Figure 8 shows the tracer test response for stochastic conductivity field 1 (variogram option 1, also see Fig. 6). Peak breakthrough time varies from 8 to more than 100 days for stochastic conductivity 1, and from 20 to 80 days for stochastic conductivity field 13.

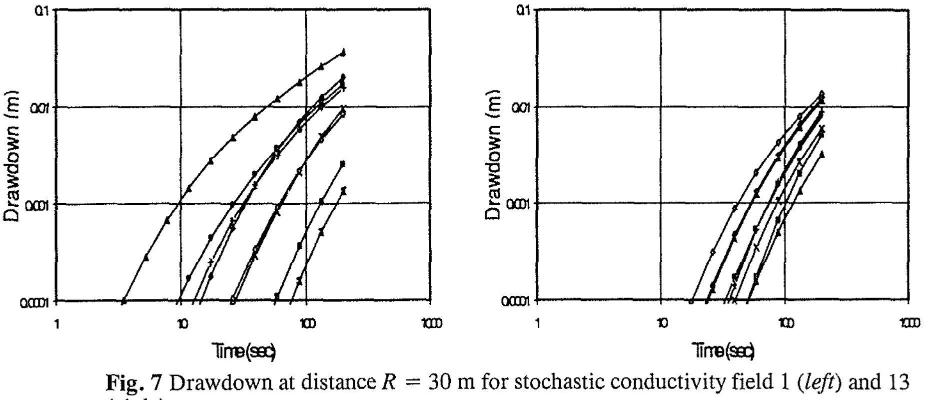


Fig. 7 Drawdown at distance R = 30 m for stochastic conductivity field 1 (*left*) and 13 (*right*).

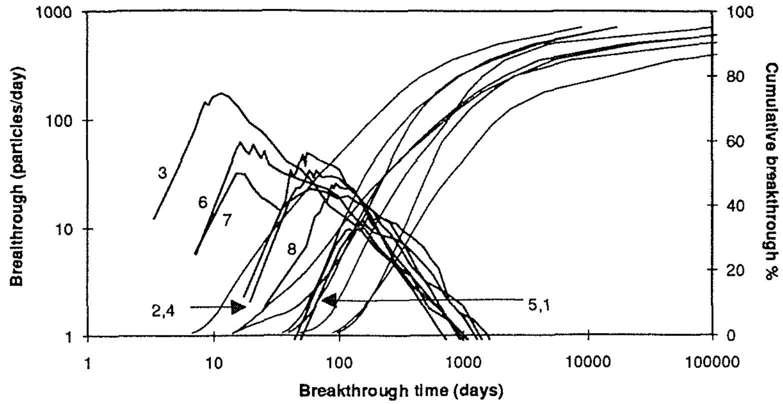


Fig. 8 Tracer breakthrough for Gaussian stochastic conductivity field 1 (numbers indicate wells where tracer was injected, also see Fig. 3).

Breakthrough curves appear to be smoother than those for the sedimentological model described earlier, but essentially a similar response is obtained.

Figure 9 shows a good correlation between the time of 5% cumulative tracer breakthrough (approximately peak breakthrough) and the time of drawdown breakthrough (the time that drawdown exceeds a given threshold set at 0.001 m). It shows that also in the Gaussian models the early time pumping test response is essentially a measure of the connectivity between pumping well and observation well. The variability of drawdown and tracer test response for the Gaussian stochastic conductivity fields (Figs 7, 8, and 9) is similar in magnitude as the variability of drawdown and tracer test response observed for the sedimentological facies model (Figs 4 and 5).

To some extent, the modelled pumping test and tracer test response allows one to distinguish between variogram options of the Gaussian stochastic conductivity fields. Figures 7 and 9 show that the strongly anisotropic variogram option 2 has a wide range

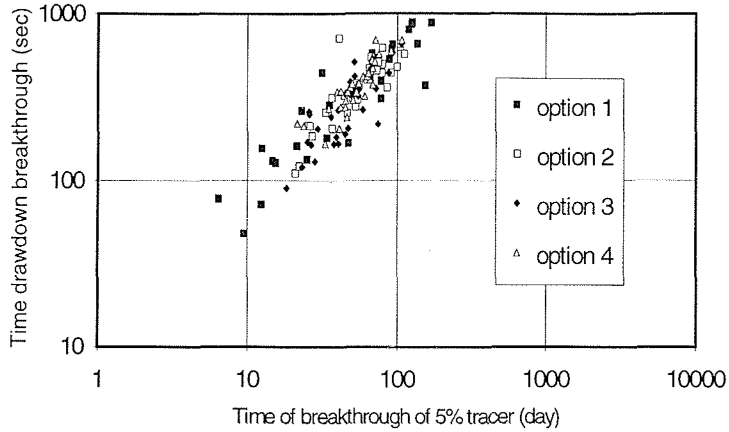


Fig. 9 Correlation between tracer breakthrough and drawdown breakthrough.

of pumping test and tracer test response, whereas the short-range isotropic variogram option 4 has a relatively narrow range of response. However, a large number of responses cluster in the middle, indicating that distinction of a variogram option (let alone a realization within an option) based on the response of a single pair of wells is extremely dangerous.

PUMPING TESTS, TRACER TESTS AND CONNECTIVITY

For the first example, the sedimentological facies model (Figs 1 and 2), the chute channel forms a highly conductive connection between the pumping well and observation well 1. Therefore it causes, during early time of a pumping test, preferential expansion of the drawdown cone into the chute channel, resulting in an anomalous early time response (earlier than average) of observation well 1 (Fig. 4).

The modelled two-well tracer test between the pumping well and well 1 reveals the fastest breakthrough (Fig. 5). The reason is that the flow velocity in the highly conductive chute channel between the pumping well and well 1 will be significantly higher than average. Analytical interpretation of the breakthrough curves presented in Fig. 5 indicate different effective porosity values, and the heterogeneity pattern does not seem to introduce significant dispersion. The very early breakthrough caused by highly conductive chute channel results in a low effective porosity, indicating that effectively only a small portion of the aquifer conducts most of the tracer from the injection well to the pumping well.

For the Gaussian geostatistical stochastic conductivity fields it is hard to pin-point connectivity, especially in three dimensions. However, the variability of early time drawdown (Fig. 7) indicates that, similarly to the chute channel of the facies model, preferential pathways occur for expansion of the drawdown cone. Both for the sedimentological facies model and the Gaussian geostatistical model a good correlation exists between the early time response of the pumping test (the drawdown breakthrough) and the initial tracer breakthrough (Fig. 9). This indicates that the variability of drawdown is a good estimator for the variability of tracer transport, and hence for connectivity. The preferential drawdown diffusion and tracer movement through the high conductivity connections can be compared with the behaviour of a fractured medium. The effective result is a small storage contributing to the early part of the pumping test, and a small effective porosity representing the limited part of the aquifer conducting the bulk of tracer.

CONCLUSIONS

- For both the sedimentological facies model and the Gaussian model connections occur which act as preferential pathways for the early expansion of the cone of drawdown (during a pumping test) and tracer flow (during a two-well tracer test).
- The early time pumping test drawdown in an observation well (drawdown breakthrough, i.e. drawdown exceeding a certain level) appears to be an excellent indicator of connectivity.

- The sedimentological facies model shows a heterogeneity effect similar to that of the Gaussian geostatistical model. In other words, the deterministic sedimentological model combined with several two-well tracer tests at different positions is a rather straightforward and efficient method to obtain an estimate of how heterogeneity affects hydraulic behaviour.
- The Gaussian geostatistical model shows a full spectrum of degrees of connectivity (expressed in the drawdown and tracer breakthrough). Therefore, it should be possible to find stochastic conductivity fields that fit a specific pumping test response. Such a selection procedure allows one to constrain the ensemble of stochastic conductivity fields using field pumping test data.
- It is impossible to systematically separate the hydraulic response for stochastic conductivity fields with significantly different variogram models. Therefore, one should be very cautious about applying inverse techniques based on a single variogram model.
- The modelled pumping tests and tracer tests demonstrate that, in the presence of heterogeneity, the early time response of a pumping test is dominated by a limited portion of the aquifer acting as preferential flow paths (also see Herweijer & Young, 1991).

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