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Effects of the investigation scale on pumping test results in heterogeneous porous aquifers

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Abstract

At the environmental field site Horkheimer Insel numerous pumping tests were performed at different investigation scales. The measured time–drawdown curves exhibit a characteristic segmentation into two or three drawdown phases. Since the site is highly heterogeneous it was intended to take advantage of the non-stationarity of the flow field during pumping tests in order to determine the effective length scale of the subsurface heterogeneity structure. The time–drawdown curves were evaluated using the Theis' analytical solution, which, however, yields different aquifer parameters for the different drawdown phases. Because this solution does not satisfy the properties of the test site aquifer totally, some of the inferred parameter distributions are regarded as suitable only for a relative comparison rather than representing 'true' effective parameters. Based on a definition of spatial and temporal scale, a statistical description along with a qualitative interpretation of the parameter distributions determined is provided. The results indicate that the effective length scale of the heterogeneity structure can be estimated from pumping test data. However, it is believed that for a quantitative interpretation of the field data, the application of numerical methods is necessary.

1. Introduction

Flow and transport in heterogeneous porous aquifers have been an issue of growing interest during the past decades. To understand and predict mass transport in such aquifers, a quantitative description of the flow field, including its variability, is a prerequisite. Therefore, considerable effort has been put into the analysis of the

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hydraulic conductivity distribution, which for many porous aquifers has been found to extend over several orders of magnitude (e.g. Gelhar, 1986; Rehfeldt et al., 1989; Schad and Teutsch, 1991). Since the spatial structure of the hydraulic conductivity of a heterogeneous aquifer cannot be completely defined using field experiments, a stochastic approach is commonly applied in modelling groundwater flow and transport in heterogeneous aquifers. The hydraulic conductivity is treated as a regionalized random variable which is characterized by its probability density function and the autocovariance function (Matheron, 1973), both of which can be estimated from experimental data. Usually there is a choice between using either a Monte–Carlo (MC) type technique for the numerical simulation of numerous equiprobable realizations of the stochastic process (e.g. Freeze, 1975; Smith and Freeze, 1979a,b) or a perturbation analysis which provides an analytical or semi-analytical solution for the stochastic differential equation (e.g. Dagan, 1981, 1982; Gelhar and Axness, 1983; Dagan, 1984; Naff, 1991). In general, the application of analytical solutions is restricted to conditions of small variance of the hydraulic conductivity distribution and for transport considerations a uniform and stationary flow field is also required. There are no such restrictions to using the computationally more expensive MC-type methods. Both approaches have in common that reliance on parameters which describe the spatial correlation of the hydraulic conductivity distribution. However, the spatial continuity of the hydraulic conductivity structure in the horizontal direction may be difficult to obtain on the basis of (vertical) borehole information alone.

This paper presents a method for the estimation of the horizontal spatial continuity of the conductivity structure within a porous aquifer based on pumping test analyses. It is part of an ongoing research project focusing on the evaluation of various sub-surface investigation methods for the characterization of heterogeneous porous systems (Hofmann et al., 1991).

Pumping tests are traditionally used for the determination of average or effective values of hydraulic parameters, such as transmissivity and storativity. (Storativity throughout this paper stands for both the elastic storage coefficient for confined conditions and specific yield for unconfined conditions.) Time–drawdown data are mostly evaluated using analytical solutions of the partial differential equation for one-dimensional radial flow under transient conditions (cf. Freeze and Cherry, 1979) and, in the case where complex boundary conditions are encountered, by numerical modelling. Analytical solutions are available for numerous hydrogeological situations and boundary conditions. A description of the methods available is given by Kruseman and de Ridder (1990). Many of these solutions are based on the unsteady state equation derived by Theis (1935) for confined, homogeneous and isotropic aquifers.

The assumption of homogeneity, inherent in many analytical solutions, makes their applicability for the investigation of heterogeneous systems at least questionable. Nevertheless it is common practice to apply such analytical models for the analysis of pumping tests in heterogeneous aquifers and to determine what are then termed effective hydraulic parameters. However, whereas pumping tests in a confined homogeneous system should always result in the same hydraulic parameters, regardless of the pumping time interval evaluated and the location of the observation wells, the values inferred from pumping test data in a heterogeneous system may vary with time and space. This is due to the transient flow regime during pumping tests, where the observed time–drawdown behaviour can be interpreted as the result of the three-dimensional scaling up of the hydraulic properties from 'point' scale values to mean or effective values, representing steadily increasing volumes of measurement during the evolution of the cone of depression. The idea in this paper therefore is, to take advantage of the non-stationarity of the flow field during pumping tests to determine the effective length scale of the subsurface heterogeneity structure.

2. Previous work

Owing to the lack of analytical solutions, radial flow in heterogeneous porous environments has usually been treated numerically in the literature. In a pioneering study, Warren and Price (1961) made a first attempt to investigate the effects of a spatially uncorrelated heterogeneous conductivity field on three-dimensional, steady-state and transient flow. They found that the effective steady-state hydraulic conductivity agreed well with the geometric mean of the model grid values. Vandenberg (1977) concluded that for a two-dimensional, uniformly distributed and also spatially uncorrelated transmissivity field, the time–drawdown behaviour agreed well with the Theis solution. The analytically obtained transmissivity values, however, came close to the arithmetic mean of the model grid values. Butler (1991) reported a stochastic analysis of pumping tests in a confined aquifer using an exponential spatial correlation of block conductivities. He concluded that for a horizontally isotropic spatial correlation of the hydraulic conductivity, the variability of transmissivity values, as determined for observation wells located at distances of up to the order of the range of the stochastic process, is insignificant with respect to their angular position. However, the variability of transmissivity values was found to increase considerably with increasing distances between observation and pumping wells. Only very few investigations based on field pumping tests in heterogeneous aquifers have been described in the literature so far. Barker and Herbert (1982) considered, in a combined numerical and experimental study, a pumping well centred in a cylindrical patch of uniform transmissivity T_1 surrounded by a matrix of transmissivity T_2. Their numerical pumping tests yielded the transmissivities T_1 and T_2 for early and late drawdown data, respectively, using an appropriate analytical solution for the evaluation of the calculated drawdown curves. Herweijer and Young (1991) presented a qualitative model of aquifer heterogeneity for the interpretation of temporal and spatial variability of hydraulic parameters derived from pumping tests in a heterogeneous fluvial aquifer.

3. Environmental field site Horkheimer Insel

The pumping tests described in this paper were performed at the environmental field site Horkheimer Insel set up in 1987/1988 in the Neckar Valley in southern

Germany (see Fig. 1). The aquifer consists of approximately 4 m of poorly sorted sand and gravel deposits of a braided river environment of holocene age. It is overlain by 5–6 m of mostly clayey flood deposits and underlain by a hydraulically tight clay and limestone formation of middle Triassic age. The alluvial sediments were found to thin out towards the Neckar Canal (see Fig. 1). The saturated thickness of the generally unconfined aquifer amounts to approximately 3 m. Under low flow conditions, the aquifer discharges to the Neckar River at a mean hydraulic gradient of about 0.001. The average regional transmissivity was determined at 3.2×10^{-2} m^2 s^{-1} from pumping tests (see following sections of this paper). For the bedrock, an approximate average conductivity of 1×10^{-6} m s^{-1} was derived from slug tests. Therefore, for most applications it can be assumed as impermeable. Hydraulic conductivity data derived from grain-size distributions using an empirical relationship (Beyer, 1964) yielded an overall variance of $\sigma^2_{\ln K} = 2.35$, thus indicating distinct heterogeneity. The site is equipped with numerous fully screened wells and multilevel piezometer nests (see Fig. 1). For the work discussed only the 5–6 inch monitoring wells within the alluvial gravel aquifer and the large diameter well (ϕ0.55 m) were taken into account.

4. Experimental work

4.1. Conceptual design

Pumping tests were carried out at the field site at intermediate investigation scales, ranging from local scale, which is in the order of the aquifer thickness (3–5 m), to the regional scale, which is in the order of the entire test site (100–200 m). Two different types of pumping tests were performed. First, 26 tests were carried out at different locations at the field site, using most of the 5–6 inch monitoring wells and the large diameter well as pumping well locations (see Fig. 1). For each of these tests, up to four surrounding wells, located at distances between 2 and 36 m from the pumping well, were monitored using automatic drawdown recording devices. A pumping duration of 2 h was chosen for each test. The pumping rate had to be adapted to the individual well yield and varied between 2 and 5.5 l s^{-1} (constant rate for each individual test). These tests are referred to as Small Scale Pumping Tests (SSPTs) throughout this paper. Secondly, a long-term pumping test was carried out at the large-diameter well (Br. 3) with a constant discharge rate of 13.6 l s^{-1} and a duration of 96 h. During this test, hereinafter referred to as Large Scale Pumping Test (LSPT), the drawdown at 23 of the 5–6 inch wells at the site was monitored.

4.2. Instrumentation for SSPTs

The SSPTs were performed at a constant discharge rate using a submersible pump in combination with a magnetic inductive flow rate meter and a control valve. High resolution of the drawdown measurements was required owing to the large transmissivity of the aquifer. This was achieved using highly sensitive piezoresistive pressure transducers. All data were recorded using a programmable data logger.

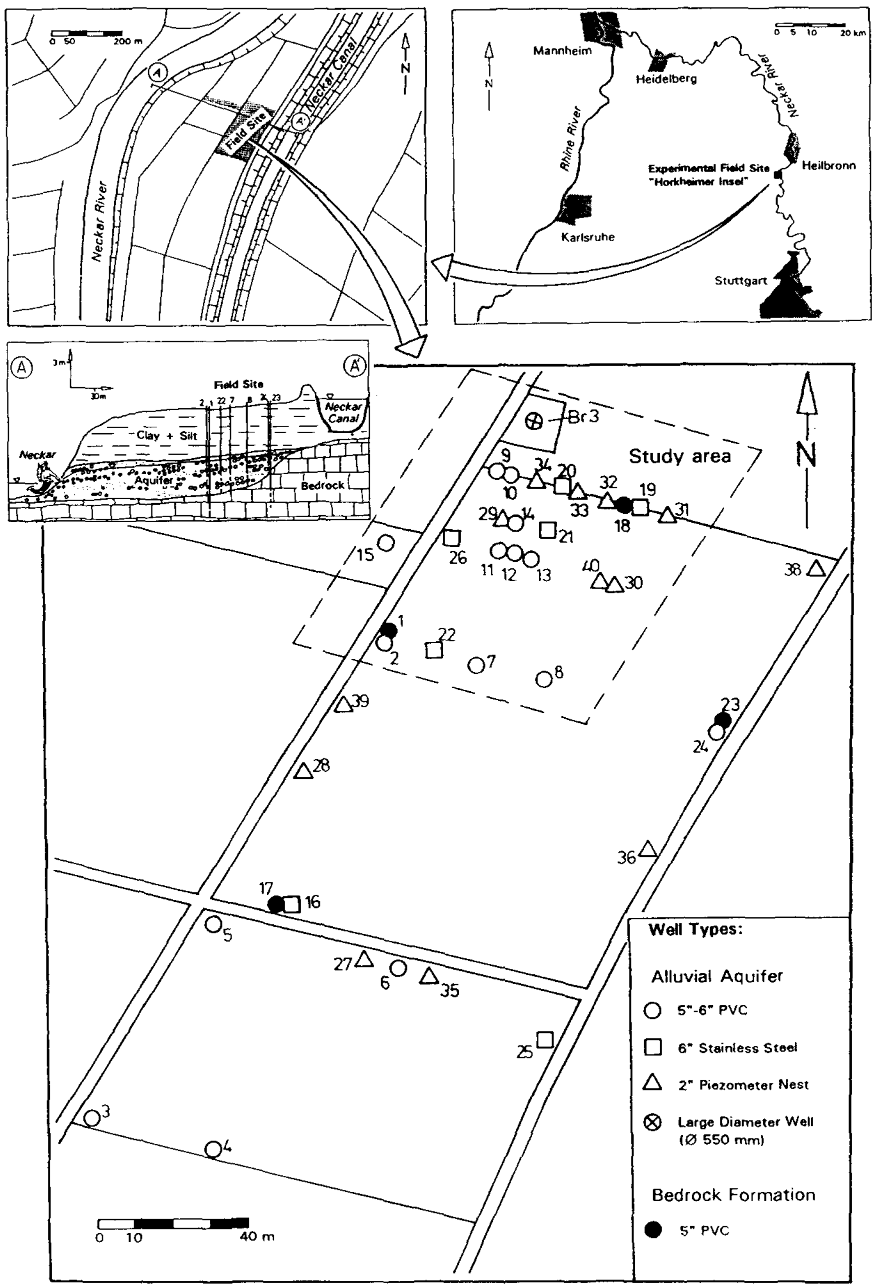

Fig. 1. Location map of the environmental field site Horkheimer Insel.

The system allows for a resolution of drawdown and time of 1 mm and 1 s, respectively.

4.3. Instrumentation for the LSPT

The LSPT was performed using ultrasonic probes for the drawdown measurements, which were recorded simultaneously at the 23 monitoring wells and stored digitally. The ultrasonic probes were installed within the water column of the observation wells at a constant depth. Maximum resolution of drawdown and time of the equipment amounts to 0.2 mm and 1 s, respectively (Dürbaum and Kohlmeier, 1970). Again, a constant pumping rate was applied using a submersible pump and a magnetic inductive flow rate meter.

4.4. Measurement results and analytical evaluation

For the following description and interpretation of the experimental data, only pumping tests performed and monitored within the northwestern part of the test site, denoted as the 'study area' in Fig. 1, were considered. From the entire data set of 26 SSPTs, the time–drawdown data of 17 tests were collected within this part of the site. Owing to well losses, the transmissivity values determined from drawdown data measured at the pumping wells proved to be significantly lower on average, compared with those determined from observation well data, and were therefore omitted. This resulted in a total of 45 drawdown curves from SSPTs. For the description and interpretation of the LSPT the drawdown data from 15 out of 23 monitoring wells were used. (The remaining eight wells are either located outside the study area or partly are screened in the underlying limestone formation only.)

On a semilogarithmic plot, time–drawdown curves of the SSPTs can be subdivided into two or three different drawdown phases. This behaviour is demonstrated in Fig. 2 for the test at well 9. The initial phase is characterized by a fast drop of the piezometric head at the pumping well location and also at the closely spaced observation well ($r = 2.1$ m). Since the radial distances of the observation wells in most cases exceed 5 m, for most SSPTs this first drawdown phase, generally lasting less than 30 s, could be observed only at the pumping well locations. The second phase is characterized by a more or less straight line section with a small slope on the semilogarithmic time–drawdown plot. This phase was observed at all monitoring wells and lasted between 10 and 30 min, depending on the distance to the pumping well. The third phase of the drawdown behaviour, lasting until the end of the SSPTs could also be approximated by a straight line section on the semilogarithmic plots, however, with a somewhat larger slope than that determined for phase two. The transition from phase two to phase three of individual curves frequently does not occur abruptly but gradually over a period of several minutes. The maximum drawdown measured at the observation wells after 2 h of pumping ranged between 0.03 and 0.1 m, depending on the radial distance to the pumping well.

Since phase one could be observed almost exclusively only at the pumping wells, only phases two and three were taken into account in a quantitative evaluation of the

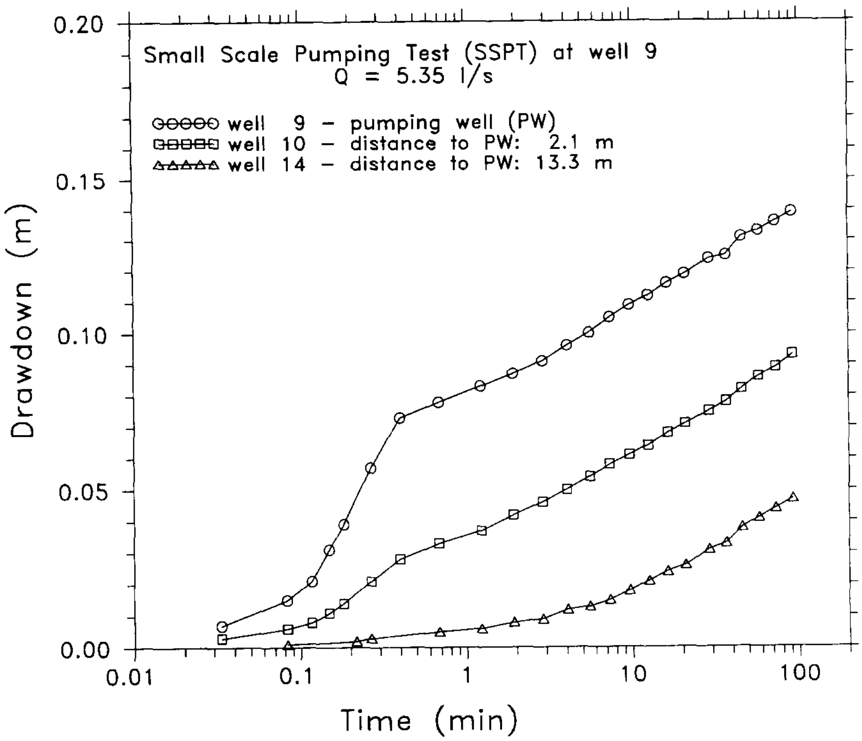

Fig. 2. Time–drawdown curves for the SSPT at well 9.

drawdown curves. It is recognized that in a heterogeneous system the application of analytical solutions, which assume homogeneity, for the evaluation of time–drawdown curves observed at different locations cannot result in one consistent set of hydraulic parameters. However, it is believed that the parameter values derived from the application of analytical solutions can be used for a comparison. The aim of this study was not, therefore, to find 'true' effective parameters of a heterogeneous system, but rather to illustrate the effects of heterogeneities on the results of the application of analytical methods. Moreover, it was intended to investigate the descriptive potential of pumping test results with respect to the heterogeneity structure of the subsurface.

An analytical solution for the time–drawdown behaviour of unconfined porous aquifers was first derived by Boulton (1954, 1963). His semiempirical solution was improved by Neuman (1972, 1975) who developed a consistent theory based on defined physical parameters only. S-shaped type curves are available for a large range of a combined aquifer geometry and anisotropy factor. The evaluation of the experimental Horkheim data using analytical methods is, however, not straight forward. The application of the 'Neuman type curve fitting method' failed owing to the missing sigmoidal shape of most of the experimental data curves. The classical type curve fitting method using the 'Theis-function' with Jacob's correction for unconfined conditions (Jacob, 1944) proved to be applicable only individually to the different segments of the drawdown curves, thus yielding different hydraulic parameters for the different phases. Both methods as well as the Cooper and Jacob (1946) straight-line method, however, yielded the same or very similar values for the late drawdown data (phase three), indicating that the flow is essentially horizontal during this phase. Therefore, the classical 'Theis type curve fitting method' was applied for the evaluation of the measured drawdown data for phase three. The hydraulic parameters transmissivity and storativity thus determined are denoted as T_3 and S_3.

Owing to the limitations and assumptions inherent in the Theis solution, it should not be applied for the evaluation of phase two. However, to derive relative numbers it was also applied for this part of the drawdown data, yielding systematically different values for the transmissivity (T_2) and storativity (S_2) compared with the corresponding values for phase three. This means that effects like vertical flow and consequently the influence of vertical anisotropy, as well as the transition from elastic response to actual dewatering resulting from the decline of the water table, are lumped into different values for the transmissivity and storativity.

The drawdown curves obtained from the LSPT (see Fig. 3) for the first 4 h of pumping generally show the same behaviour as those obtained from the SSPTs. Again two (at the pumping well three) phases of drawdown can be distinguished; however, the transition between them is smoother than for the SSPTs. As for the evaluation of the SSPTs, the transmissivity and storativity for phases two and three were determined individually using the method of Theis. From 4 h after pumping

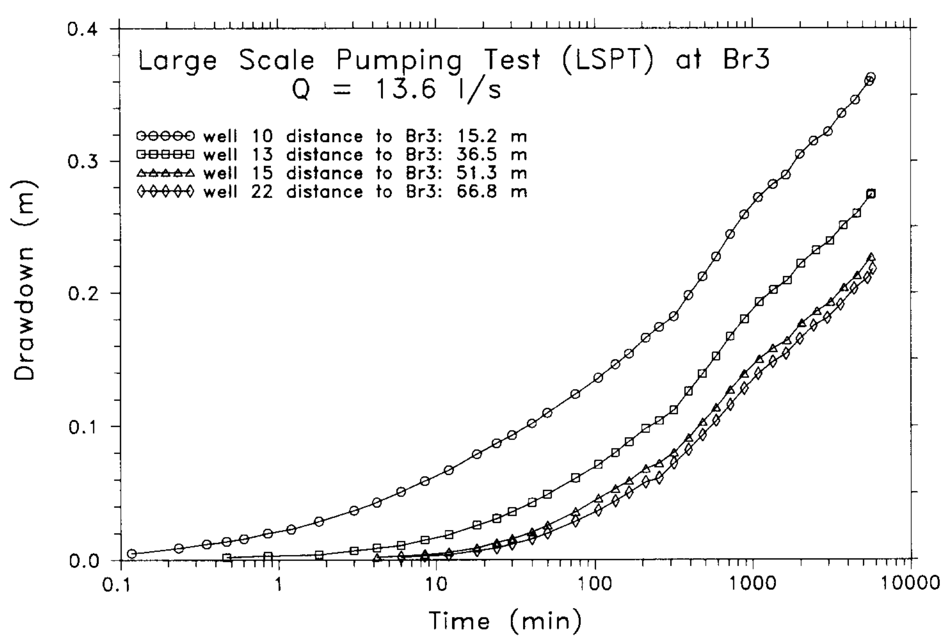

Fig. 3. Time–drawdown curves of the LSPT for four monitoring wells located at different distances from the pumping well Br. 3.

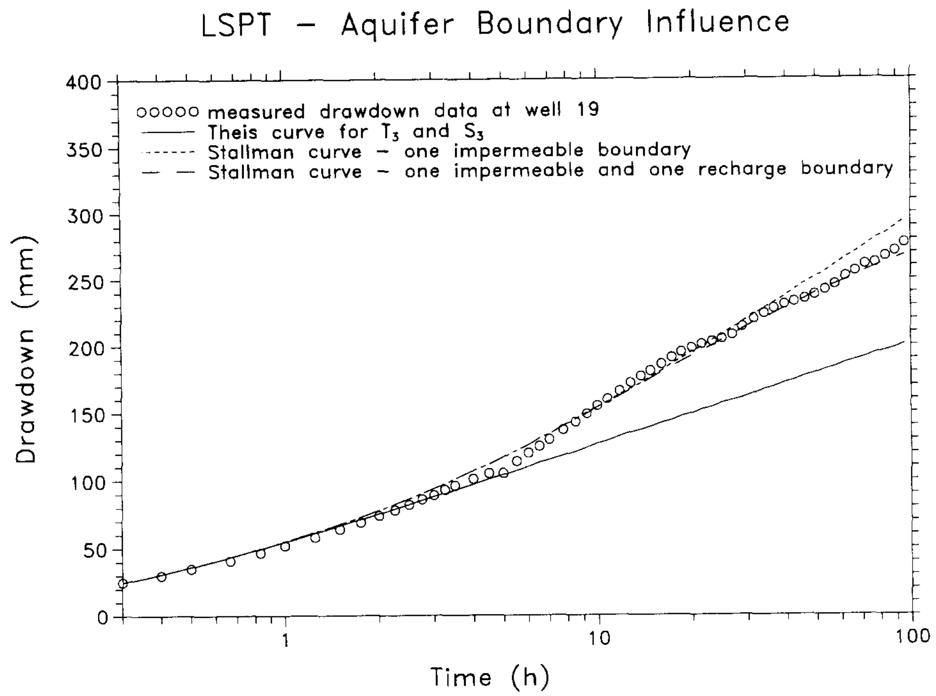

Fig. 4. Measured vs. calculated drawdown for well 19, considering different boundary conditions for the LSPT at Br. 3.

started until the end of the test, the measured drawdown data deviate from the behaviour predicted by the Theis solution using T_3 and S_3 determined for each observation well. On a semilogarithmic plot (see Fig. 4), the slope of the data curve first increases and after about 20 h of pumping slightly decreases again. This effect is interpreted as the influence of the lateral aquifer boundaries on the time–drawdown behaviour (see schematic cross-section in Fig. 1). It can be reproduced by applying the Stallman solution (in Ferris et al., 1962) and introducing an impermeable boundary at a distance of approximately 100 m east from the pumping well and a recharge boundary (Neckar river) at a distance of approximately 200 m in opposite direction. Fig. 4 shows the effect of the two boundaries at observation well 19. The first boundary starts to affect the drawdown after approximately 3 h of pumping. This also demonstrates that the entire drawdown phase three of the SSPTs is influenced only by inherent aquifer properties and not by the aquifer boundaries. For the recharge boundary, an efficiency reduction factor of 0.3 was determined by curve fitting. This implies that the discharge or recharge rate of every image well of this boundary is reduced by this factor. One possible physical explanation of this efficiency reduction factor could be leakage resistance of the Neckar River bed. Applying this modification, a reasonable fit of the analytical solution, taking into account the two parallel aquifer boundaries, could be achieved for all drawdown curves using the respective transmissivity and storativity values determined for phase three.

5. Statistical description

Table 1 lists the basic statistical parameters for the hydraulic parameter sets determined. Owing to the overlapping network of the volumes of integration for which the parameter values were determined, the individual values cannot be regarded as spatially independent. Thus, the total variance of the transmissivity and storativity cannot be estimated from the parameter distributions given.

The variability of the different parameter distributions can be expressed in terms of their coefficients of variation (CV). A temporal analysis shows that, except for the storativity values determined for the LSPT, the calculated CV values are consistently lower for phase three than for phase two. This averaging effect, which is due to the increase of the volumes of influence during pumping tests, also becomes evident from a spatial analysis. The coefficient of variation was found to be generally lower for the parameter sets of the LSPT than for the corresponding distributions of the SSPTs. This, however, probably not only is due to a larger mean radial distance between the observation and pumping wells for the LSPT compared with the SSPTs, but also to a more complete overlapping of the volumes of influence for the observation wells of the LSPT (only one pumping test location). The LSPT data should therefore show a higher degree of spatial correlation as compared with the SSPT data.

A comparison of the parameter mean values for the SSPTs and the LSPT demonstrates first the general finding that $T_2 > T_3$ and $S_2 < S_3$ for both types of tests. Secondly, the temporal variation of the mean values of both parameters, transmissivity and storativity, is much smaller for the LSPT than for the SSPTs. This is expressed by the differences between corresponding mean values for phases two and three (e.g. $\Delta T_{\mathrm{temporal}}(\mathrm{SSPT}) = \bar{T}_{2,\mathrm{SSPT}} - \bar{T}_{3,\mathrm{SSPT}}$ and $\Delta S_{\mathrm{temporal}}(\mathrm{SSPT}) = \bar{S}_{2,\mathrm{SSPT}} - \bar{S}_{3,\mathrm{SSPT}}$). For both parameters (see Table 2), the difference for the LSPT is less than half of that calculated for the SSPTs. The same type of comparison can be performed with respect to the spatial variation of the mean values by calculating the

Table 1
Basic statistical parameters for the determined transmissivity and storativity distributions for drawndown phases two and three for SSPTs and the LSPT

Parameter	SSPTs				LSPT			
Number of tests performed		17				1		
Number of evaulated drawndown curves		45				15		
	Min	Mean	Max	CV[c]	Min	Mean	Max	CV[c]
Radial distances PW[a] – OW[b]	2.1	17.8	36.0		15.2	40.6	70.6	
Transmissivity for phase two ($m^2 s^{-1}$)	0.016	0.115	0.32	0.585	0.042	0.065	0.13	0.35
Transmissivity for phase three ($m^2 s^{-1}$)	0.024	0.034	0.05	0.186	0.029	0.032	0.035	0.069
Storativity for phase two (-)	0.00058	0.021	0.1	1.05	0.018	0.035	0.058	0.34
Storativity for phase three (-)	0.017	0.066	0.13	0.466	0.026	0.05	0.11	0.37

[a] PW is the pumping well.
[b] OW is the observation well.
[c] CV is the coefficient of variation (standard deviation/mean).

Table 2
Differences of the mean values of the transmissivity and storativity distributions for phases two and three and for SSPTs and the LSPT

Parameter	Phases 2–3		SSPTs – LSPT		Parameter
	SSPT	LSPT	Phase 2	Phase 3	
$\Delta T_{\text{temporal}}$[a]	0.081	0.033	0.05	0.002	$\Delta T_{\text{spatial}}$[c]
$\Delta S_{\text{temporal}}$[b]	−0.045	−0.015	−0.014	0.016	$\Delta S_{\text{spatial}}$[d]

[a] The difference of mean transmissivities for phases two and three.
[b] The difference of mean storativities for phases two and three.
[c] The difference of mean transmissivities for SSPTs and the LSPT.
[d] The difference of mean storativities for SSPTs and the LSPT.

difference between corresponding mean values for the SSPTs and the LSPT (e.g. $\Delta T_{\text{spatial}}$(phase two) $= \bar{T}_{2,\text{SSPT}} - \bar{T}_{2,\text{LSPT}}$ and $\Delta S_{\text{spatial}}$(phase two) $= \bar{S}_{2,\text{SSPT}} - \bar{S}_{2,\text{LSPT}}$). This yields a large value for $\Delta T_{\text{spatial}}$ for phase two (see Table 2). The mean transmissivity for phase three, however, can be regarded as independent of the distance between pumping and observation wells ($\Delta T_{\text{spatial}}$(phase three) $= 0.002$). The spatial variation of the mean storativity values is different for phase two and phase three. For phase two the mean is lower for the SSPTs, whereas for phase three it is lower for the LSPT.

Summarizing the statistical description, characteristic differences between the individual parameter sets could be observed. This applies to both the different types of tests carried out and the different drawdown phases considered in the analytical evaluation.

6. Discussion

Following the definition of heterogeneity given by Greenkorn and Kessler (1969), heterogeneous aquifers may be classified into two groups. The first one comprises systems with finite bodies of sediments embedded into a continuous matrix of different composition. The second group represents aquifer systems with several types of sedimentary structures none of which constitute a continuous background matrix. For both groups, one has to assume different hydraulic properties for different types of sediments (e.g. gravel lenses, sand bodies, silt and clay layers). Within individual sedimentary units, the hydraulic conductivity distribution can be assumed homogeneous with only minor variability, whereas for the entire aquifer a possibly bi- or multimodal hydraulic conductivity distribution with a much larger variance can be observed. At the 'intrasedimentary unit scale', there may still exist considerable anisotropy. Because fluvial sedimentary structures are commonly more continuous in horizontal than in vertical directions, heterogeneity also introduces anisotropy to the hydraulic parameter field at the larger, 'intersedimentary unit scale'. At the regional scale, in many cases the entire aquifer can be considered as quasi-homogeneous with an effective anisotropy resulting from the smaller scale anisotropy and heterogeneity.

The different sedimentary structures can be characterized by a statistical description of the distributions of their hydraulic properties and by a spatial autocovariance function of a parameter characteristic of these structures. Both of these may be different for different types of sedimentary structures. Owing to the non-stationarity of the flow field during a pumping test, the temporal and consequently also spatial evolution of the piezometric head distribution is affected by the heterogeneity and anisotropy of the aquifer at the different scales of investigation. The drawdown for a given time and location, therefore, represents the temporally and spatially integrated physical response of the aquifer to the discharge at the well. It follows that parameters determined from pumping tests depend on the location and the pumping time interval for which the data were collected. Assuming large-scale statistical stationarity of the hydraulic parameter fields, this conclusion applies mainly to distances between pumping and observation wells, similar to the characteristic length of the sedimentary structures.

The transmissivity and storativity values for both drawdown phases and for both types of tests are shown in Figs. 5 and 6 as a function of the radial distance between pumping and observation wells. Both figures depict the variability of the different parameter sets as described above. A qualitative and preliminary physical explanation for the hydraulic parameter distributions observed is given below.

6.1. Variability of transmissivity

As shown in Fig. 5 as well as in Tables 1 and 2, the transmissivity values for phase

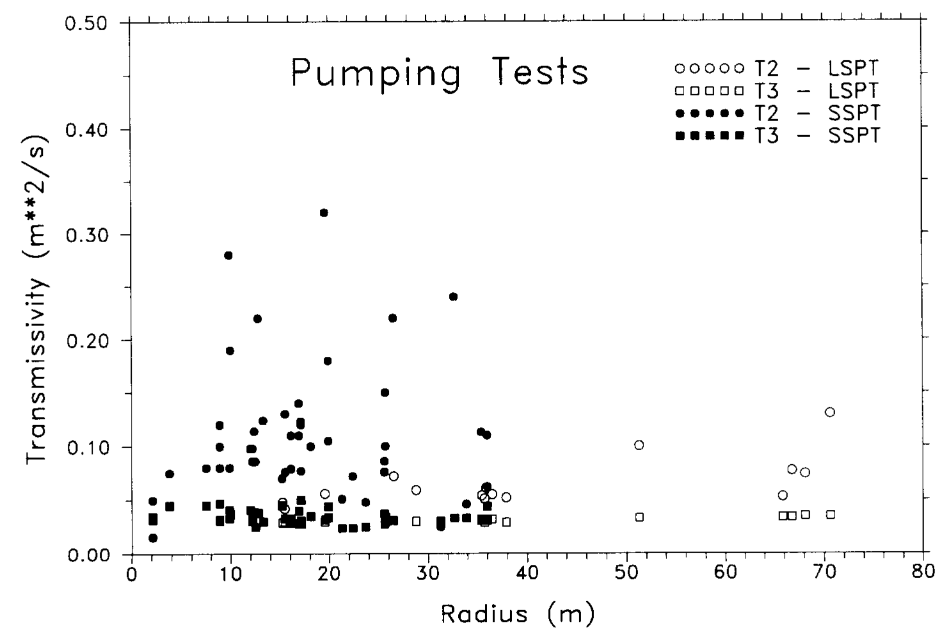

Fig. 5. Transmissivity values determined for drawdown phases two and three for SSPTs and the LSPT.

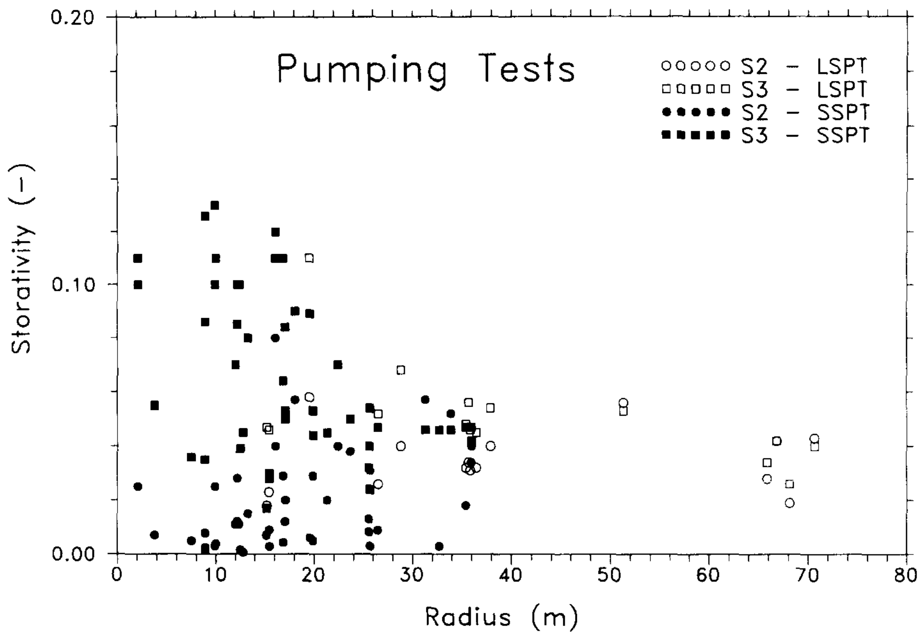

Fig. 6. Storativity values determined for drawdown phases two and three for SSPTs and the LSPT.

two are generally larger than those determined for phase three. The variability of T-values is largest for phase two of the SSPTs and lowest for phase three of the LSPT. Both findings can be explained by temporal and spatial scaling up (averaging) of the hydraulic conductivity field, which in a spatially correlated heterogeneous aquifer leads to different effective values for different time intervals and observation distances.

6.1.1. SSPTs — phase two

In the case where pumping and observation wells are closely spaced, highly conductive zones in the near vicinity of the wells have a large influence on the drawdown measured at the observation well. When pumping starts, the disturbance (drawdown at the pumping well) propagates radially into the aquifer. The velocity at which it propagates depends on the hydraulic diffusivity $D = T/S$. Because the variability of T or K is usually much larger than the variability of S, diffusivity is large for highly conductive zones and small for low conductivity zones. At the beginning of a pumping test, a vertical hydraulic gradient from lower to higher conductive zones is induced in the vicinity of the pumping well. Therefore, the highly conductive zones may be regarded as drainage structures or as lateral extensions of the well bore for the early drawdown phase. Hence, the effective transmissivity for the early drawdown phase is determined largely by the location and the conductivity of higher permeable zones in the vicinity of the pumping well. This explains the large effective mean transmissivity for phase two of the SSPTs. The large variability of T-values for phase two ($CV(\mathrm{SSPT}, T_2) = 0.585$) is believed to be due mainly to spatial variability in connection with different pumping well locations.

6.1.2. SSPTs — phase three

With increasing pumping time, vertical flow becomes negligible at short distances. Flow is mainly horizontal and less conductive areas contribute more to the effective transmissivity than at the early stage of drawdown. This results in a considerably lower mean transmissivity for phase three of the SSPTs than for phase two. The decrease of the variability of the effective transmissivity values for the SSPTs with time ($CV(\mathrm{SSPT}, T_3) = 0.186$ vs. $CV(\mathrm{SSPT}, T_2) = 0.585$) is believed to be due to increasing volumes of influence with increasing pumping time. Effective transmissivity values for late drawdown data (phase three) are representative for larger areas than the values for phase two and are, therefore, less dependent on small-scale local properties.

6.1.3. LSPT — phase two

Hydraulic conductivity structures in heterogeneous aquifers are not horizontally continuous but of finite extension. Owing to different mean radial distances between pumping and observation wells (40.6 m for the LSPT and 17.8 m for the SSPTs), the process of spatial scaling up yields a lower average for the transmissivity values for phase two of the LSPT than for phase two of the SSPTs. The corresponding parameter variability is much smaller for the LSPT than for the SSPTs. This can be explained partly by an implicitly higher degree of spatial averaging for the drawdown measurements of the LSPT owing to larger distances to the pumping well and partly by different numbers of pumping well locations for both types of tests. The drawdown measurements of the LSPT with only one pumping test location are spatially more dependent than those of the SSPTs with numerous different pumping well locations.

6.1.4. LSPT — phase three

The effective transmissivity values for phase three of the LSPT also show a smaller variability than those determined for the SSPTs ($CV(\mathrm{LSPT}, T_3) = 0.069$ vs. $CV(\mathrm{SSPT}, T_3) = 0.186$) for the same reasons as stated for phase two. The mean transmissivity values for phase three of the SSPTs and LSPT, however, differ only slightly. This indicates that transmissivity values determined from late drawdown data are independent of the distance between pumping and observation wells and may be considered as the effective transmissivity of the test site aquifer.

6.2. Variability of storativity

The storativity distributions shown in Fig. 6 exhibit different characteristics compared with the corresponding transmissivity distributions discussed above. First, on average storativity values determined for drawdown phase two are significantly lower than corresponding values for phase three (see Table 1). Secondly, variability is largest for S_2 values of the SSPTs and about equally low for both phases of the LSPT, with a somewhat larger mean for phase three ($\bar{S}_{2,\mathrm{LSPT}} = 0.035$ vs. $\bar{S}_{3,\mathrm{LSPT}} = 0.05$). For the interpretation of the parameter variability encountered not only the effects of heterogeneity but also the 'delayed yield effect' have to be taken into account. Delayed yield generally occurs in unconfined aquifers during the early stage of drawdown.

6.2.1. SSPTs — phase two

According to the concept of delayed yield (Neuman, 1972) water is released at first from elastic storage when pumping starts. Time–drawdown curves follow the 'Theis type curve' for confined conditions (elastic storage). Owing to a generally small ratio of S/S_y (S is the elastic storage coefficient, S_y is the specific yield), a vertical gradient develops, which creates a temporary flattening of the time–drawdown curves. After this intermediate phase, the drawdown curves again follow the Theis type curve, but now for unconfined conditions (specific yield). Depending on r/b (r is the distance between pumping and observation wells, b is the aquifer thickness) and aquifer properties, such as, e.g. vertical anisotropy, the early part of the delayed yield effect may not be recognized in field drawdown data. For the present test site aquifer, r/b for most observation wells is larger than 5. This leads to time–drawdown curves which start at some point on the intermediate flat part of the Neuman type curves followed by data points which fit reasonably well on the Theis type curve for unconfined conditions. The storativity values determined for phase two therefore have to be regarded as semiquantitative, representing the transition from elastic storage to specific yield. This results in a large variability of S_2 values with lower values for short distances and larger values for larger observation distances. Thus, the observed parameter variability is believed to be due mainly to the delayed yield effect.

6.2.2. LSPT — phase two

Compared with the S_2 distribution for the SSPTs, the S_2 values for the LSPT are significantly less variable ($CV(\text{LSPT}, S_2) = 0.34$ vs. $CV(\text{SSPT}, S_2) = 1.05$) and show a larger mean. Owing to larger observation distances (large r/b), delayed yield is not as obvious from the storativity values for the early drawdown phase of the LSPT, which is still consistent with Neuman's physical model for delayed yield.

6.2.3. SSPTs and LSPT — phase three

As described above the drawdown data for phase three generally follow a quasi-straight line on a semilog time–drawdown plot. Transmissivity values determined for this phase were independent of the distance between pumping and observation wells. From Fig. 6, it is obvious that this does not apply to the storativity values, which for phase three have to be interpreted as specific yield (i.e. effective porosity). They showed a large variability for short observation distances and a successively smaller variability for larger distances. The explanation for this relationship has in principle already been given in the discussion of the temporal and spatial variability of the transmissivity values. For the early stage, aquifer heterogeneities have maximum influence on the spatial variability of drawdown. Suppose that two observation wells are located at the same distance from a pumping well but in different directions, one of them being connected with the pumping well by a highly conductive zone. This well will respond earlier than the second observation well to the onset of the discharge at the pumping well. This is due to the larger hydraulic diffusivity in the area of the more permeable zone. The difference in drawdown will persist also during later times (phase three). Whereas the transmissivity values for phase three are determined from the slope of the semilog time–drawdown plot and therefore may be identical for both observation wells, the corresponding storativity values, which always depend on the entire history of drawdown prior to the time interval evaluated, will be different. Owing to the different early stage drawdown behaviour, the later drawdown data (phase three) for the observation well connected with the pumping well via a highly conductive zone will plot parallel to the time–drawdown curve for the other well. This results in a smaller value for t_0 (point of intersection with the time axis) for the first well and therefore in a larger storativity value.

This qualitative physical model appears to be suitable for the explanation of the observed variability of S_3 values. For short distances, the heterogeneity effect described will be largest on the 'effective' storativity for phase three. For larger distances, spatial averaging will tend to smooth out the local variability. The variability of S_3 values, therefore, is believed to give an estimate of the length of highly permeable lenses. For the present case study, this length scale can be estimated to be approximately 25 m. In geostatistical terms it appears more appropriate to relate this measure to the range rather than to the integral scale.

7. Conclusions

The experimental study indicates that by using analytical solutions developed for homogeneous systems, valuable information about the structure and the scaling up behaviour of heterogeneous porous aquifers can be inferred from pumping test data. The resulting parameter distributions, however, have to be considered as semi-quantitative, owing to the mismatch of the assumptions in the analytical model and the aquifer properties encountered. In a forthcoming second step, a numerical study will be performed to extend this to a fully quantitative investigation of the effects of, e.g. size, shape, location of highly permeable zones and hydraulic parameter variability on the time–drawdown behaviour at different distances to a pumping well. This may include a boolean type flow model with highly permeable structures within a uniform and less conductive matrix and as a second step, the development of a stochastic model to provide a probabilistic framework for the interpretation of the field data.

8. References

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