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Estimating parameters of aquifer heterogeneity using pumping tests – implications for field applications

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ABSTRACT

The knowledge of subsurface heterogeneity is a prerequisite to describe flow and transport in porous media. Of particular interest are the variance and the correlation scale of hydraulic conductivity. In this study, we present how these aquifer parameters can be inferred using empirical steady state pumping test data. We refer to a previously developed analytical solution of “effective well flow” and examine its applicability to pumping test data as under field conditions. It is examined how the accuracy and confidence of parameter estimates of variance and correlation length depend on the number and location of head measurements. Simulations of steady state pumping tests in a confined virtual aquifer are used to systematically reduce sampling size while determining the rating of the estimates at each level of data density. The method was then applied to estimate the statistical parameters of a fluvial heterogeneous aquifer at the test site Horkheimer Insel, Germany. We conclude that the “effective well flow” solution is a simple alternative to laboratory investigations to estimate the statistical heterogeneity parameter using steady state pumping tests. However, the accuracy and uncertainty of the estimates depend on the design of the field study. In this regard, our results can help to improve the conceptual design of pumping tests with regard to the parameter of interest.

1. Introduction

The vast majority of natural aquifers are characterized by discontinuities, which evolved from geological processes. Heterogeneity in the sedimentary composition as well as structural aspects like fissures, fractures, and facies transitions result in spatial heterogeneity of hydraulic properties. Based on statistical parameters, geostatistical distributions have been suggested and tested on field data to describe these hydraulic aquifer heterogeneities. The variance and the correlation scale of the hydraulic conductivity are of particular interest, since they determine the transport characteristics of solutes and their mixing which is critical for contaminant migration and in-situ remediation.

Variance and correlation scale are usually determined by tedious field site characterizations. This is related to a high amount of effort and costs since a huge number of point measurements is needed to estimate the correlation length from geostatistical variogram analysis [1]. Thus, there is a need for alternative approaches to infer parameters of aquifer statistics from well-established test methods and thereby reduce time and cost-loads, which are involved with extensive laboratory investigations.

A Ground water pumping test is a well-established tool to estimate the mean hydraulic conductivity of the area of influence of the pumping test drawdown. Classical interpretation methods base on Thiem’s formula [2] or Theis’ solution [3] for steady state or transient flow conditions, respectively; the latter having been simplified by [4]. Detailed information on the application of those approaches under numerous boundary conditions is provided by [5].

These interpretation methods build upon the simplifying assumption of homogeneous systems or simplified systems comprising of few homogeneous units. However, the non-uniformity of aquifer properties affect the drawdown curve of pumping tests [6]. A constant representative conductivity value is inadequate to describe the flow toward the pumping well, since distinct representative values emerge for the flow near and far from the pumping well [7,8].

Only a hydraulic conductivity field based on a radial distance dependent function is capable to capture the drawdown behavior in heterogeneous media effectively. Moreover, this function has to depend on the variance and correlation scale. Most of the studies describe well flow in two-dimensional heterogeneous porous media, thereby representing large scale pumping tests [9–18]. For small scale pumping tests, vertical flow in the vicinity of the pumping well is a

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critical component that influences the drawdown. Hence, a three dimensional representation of the aquifer is needed, which has only been considered in a few studies [19–24].

In general, these methods can be used to infer the variance and correlation scale using pumping test data, involving two challenges: (i) The description of the radially depending hydraulic conductivity or the head drawdown implicitly depends on the variance and correlation scale, thereby inhibiting the inverse estimation of these parameters; (ii) The applicability of the method to pumping test field data needs to be assessed. To our knowledge, the methods above have only been applied to asses virtual aquifers.

Regarding the first challenge, the study of [24] overcomes this limitation, since it provides an analytical description of the vertical mean drawdown of a steady state pumping test in three dimensional heterogeneous porous media. The analytical solution of effective well flow $h^{\mathrm{efw}}(r)$ depends explicitly on the statistical properties of hydraulic conductivity, such as the mean, the variance, the horizontal correlation length, and the anisotropy ratio. Unlike most methods related to hydraulic tomography [25,26] or transient pumping-tests [27,28], the method of effective well flow is not an inversion strategy. Instead, the goal is to estimate the statistical heterogeneity parameters directly using steady state head measurements without explicitly reconstructing the heterogeneously distributed field of hydraulic conductivities.

The second challenge is in interpretation of pumping test data from field studies since the numbers of drawdown measurements is limited in space and time. The performance of methods developed to interpret pumping tests in heterogeneous media need to be tested with regard to the number and location of measurements as under field-site conditions. In contrast to simulated pumping tests in virtual aquifers, the underlying conductivity distribution of natural aquifers is unknown, which hampers the qualitative assessment of parameter estimates. Moreover, the limited number of locations for head measurements involve uncertainty in parameter estimates, e.g. if pumping tests are by chance conducted in areas of much higher or lower than average conductivity.

The aim of this study is to close the gap between theory and field application for the method of effective well flow. We demonstrate how the method can be applied to estimate the statistical aquifer parameters using steady state pumping test field data.

As a first step (Section 3), we examine the capability and predictive power of the method to provide parameter estimates for a limited number of observation points. We analyze virtual pumping tests by reducing the sample size of head measurements and evaluating the quality of parameter estimation. We focus on small scale pumping tests, for which vertical flow needs to be taken into account and simulations are performed in three dimensions.

In a second step (Section 4), we apply the method to aquifer test data from the Horkheimer Insel test site in Germany in order to estimate the aquifer statistics as cost-efficient alternative to laboratory investigations and field methods for the estimation of statistical aquifer parameters [29–31]. The field site has been intensively examined in multiple field campaigns [32–34] including sedimentological characterization based on a large number of core samples collected at the site [35].

Eventually, we conclude with recommendations regarding the conceptual design of pumping tests. The results further allow to determine the predictive power of pumping test data from established test sites with regard to the estimation of parameters of aquifer heterogeneity.

2. Theoretical framework

This study is based on the concept of effective well flow head $h^{\mathrm{efw}}(r)$ [24]. The relationship between $h^{\mathrm{efw}}(r)$ and the hydraulic head for pumping tests, conducted in heterogeneous porous media, is depicted in Fig. 1. Moreover, the fundamentally distinct method of predicting the hydraulic head of homogeneous aquifers using Thiem's solution is illustrated.

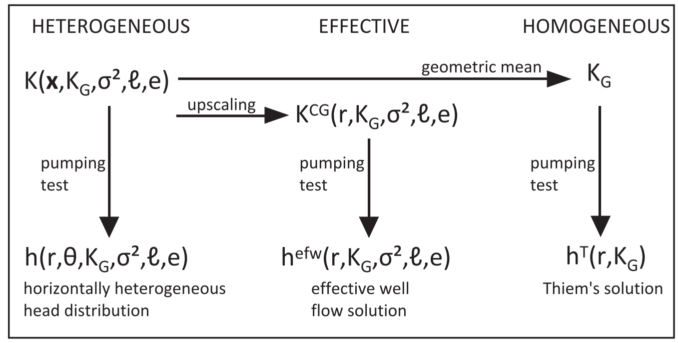

Fig. 1. Relation between hydraulic conductivities and hydraulic heads for well flow based on the method of deduction: heterogeneous ($K(\vec{x})$ and $h(r,\theta)$), effective ($K^{\mathrm{CG}}(r)$ and $h^{\mathrm{efw}}(r)$), and homogeneous (K_{G} and $h^{\mathrm{T}}(r)$).

Starting point is a spatially distributed heterogeneous, anisotropic conductivity field $K(\vec{x})$. It is modeled as spatial random function with log-normally distributed values $K(\vec{x}) \propto \mathcal{LN}(\mu, \sigma^2)$, where μ and σ^2 denote the mean and variance of the normal distribution $\ln K(\vec{x})$, respectively. $K(\vec{x})$ can be statistically described by the geometric mean $K_G = \exp\mu$, the variance σ^2, the correlation length ℓ, and the anisotropy ratio between the vertical and the horizontal correlation $e = \ell_v/\ell$, which are representative parameters of the entire aquifer under consideration. Conducting pumping tests in such an aquifer results in a spatially distributed hydraulic head field $h(r,\theta)$, depending on the statistical parameters of $K(\vec{x})$. Tracing back the parameters of $K(\vec{x})$ from the heterogeneous drawdown is the fundamental goal of estimating aquifer parameters inversely.

The approach of [24] is based on adapted spatial averaging of $K(\vec{x})$ according to the conditions of pumping tests. Using the upscaling procedure coarse graining [16,36], a representative conductivity $K^{\mathrm{CG}}(r)$ is derived, which depends on the statistical parameters K_{G}, σ^2, ℓ, and e of $K(\vec{x})$ rather than being fully homogenized.

Coarse Graining can be best explained as a spatial filtering approach that averages over volumes of variable filter sizes. Applied to pumping tests, coarse graining accounts for the character of radial convergent flow. For observation points located near the well, where the impact of heterogeneity is large, the filter size is adjusted such as that small volumes are captured, thereby leaving the heterogeneity nearly unchanged. By contrast, far from the pumping well, the filter size is larger resulting in averaged values of the hydraulic conductivity.

Pumping tests conducted in a $K^{\mathrm{CG}}(r)$-field result in values of $h^{\mathrm{efw}}(r)$ (Fig. 1) that reproduce the vertically averaged hydraulic head $h(r,\theta)$ of a heterogeneous medium very well, because $K^{\mathrm{CG}}(r)$ captures effects of the heterogeneity, in contrast to Thiem's solution $h^{\mathrm{T}}(r)$.

2.1. The effective well flow head

The analytical solution of the effective well flow head $h^{\mathrm{efw}}(r)$ can be considered as an extension of Thiem's solution to heterogeneous media [24]. It reproduces the vertical mean drawdown of a steady state pumping test in relation to the radial distance r and the statistical parameters of $K(\vec{x})$:

$$h^{\mathrm{efw}}(r) = \tilde{C}\exp(-\chi)\ln\frac{r}{R} + \tilde{C}\sinh(\chi)U_1(r) + \tilde{C}(1-\cosh(\chi))U_2(r) + h(R), \quad (1)$$

with

$$U_1(r) = \ln\frac{u(r)+1}{u(R)+1} - \frac{1}{u(r)} + \frac{1}{u(R)} \quad (2)$$