Journal of Hydrology 511 (2014) 310–319

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Data processing for oscillatory pumping tests

Tania Bakhos [a,*], Michael Cardiff [b], Warren Barrash [c], Peter K. Kitanidis [d,a]

[a] Institute for Computational and Mathematical Engineering, Jen-Hsun Huang Engineering Center, Stanford, CA, United States
[b] Department of Geoscience, University of Wisconsin-Madison, Madison, WI, United States
[c] Center for Geophysical Investigation of the Shallow Subsurface, Department of Geosciences, Boise State University, Boise, ID, United States
[d] Department of Civil and Environmental Engineering, Yang and Yamazaki Environment and Energy Building, Stanford, CA, United States

ARTICLE INFO

Article history:
Received 27 June 2013
Received in revised form 3 January 2014
Accepted 5 January 2014
Available online 13 January 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Nunzio Romano, Associate Editor

Keywords:
Periodic signals
Aquifer characterization
Oscillatory pumping tests
Data processing

ABSTRACT

Characterizing the subsurface is important for many hydrogeologic projects such as site remediation and groundwater resource exploration. Methods based on the analysis of conventional pumping tests have the notable disadvantage that at a certain distance, the signal is small relative to the noise due to the effects of recharge, pumping in neighboring wells, change in the level or adjacent streams, and other common disturbances. This work focuses on oscillatory pumping tests in which fluid is extracted for half a period, then reinjected. We discuss a major advantage of oscillatory pumping tests: small amplitude signals can be recovered from noisy data measured at observation wells and quantify the uncertainties in the estimates. We demonstrate results from a joint inversion of storativity and transmissivity. We conclude with an analysis of the duration of the initial transient, providing lower bounds on the length of elapsed time until the effects of the transient can be neglected.

© 2014 The Authors. Published by Elsevier B.V. Open access under CC BY-NC-ND license.

1. Introduction

Subsurface imaging, or determining important hydraulic parameters such as spatially-distributed hydraulic conductivities (K) and specific storage (S_s), remains an important challenge in hydrology. Various pressure-based methods, i.e., methods that use changes in head or flow rate as the primary source of measurements, have been used to obtain an image of the 3-D heterogeneity of the flow parameters. Examples of such methods include partially penetrating slug tests (e.g. Bouwer and Rice, 1976, Butler (1998), Cardiff et al. (2011), and Zlotnik and McGuire (1998)), direct push methods (e.g. Dietrich and Leven (2009), Butler et al. (2002)) and borehole flow meters (e.g. Hess (1986), and Paillet (1998)).

Hydraulic tomography (Hao et al., 2007; Illman et al., 2009; Yeh and Liu, 2000) is an imaging method that uses data from aquifer tests in which the pressure is changed at several distinct locations and the measurements of pressure responses at many locations in the aquifer are recorded. Inversion of the resulting data set provides an estimate of 3-D spatially heterogeneous flow parameters (Gottlieb and Dietrich, 1995). One example of such a method is transient hydraulic tomography (Zhu and Yeh, 2005; Cardiff et al., 2012; Berg and Illman, 2011; Xiang et al., 2009). A more comprehensive review of publications on research related to hydraulic tomography is offered by Cardiff and Barrash (2011).

A difficulty associated with traditional pumping and slug tests and also hydraulic tomography based on these tests is that the signal weakens with distance and, after a certain point becomes submerged in the ambient noise. The hydraulic head is sensitive to external changes, such as changes in the level of rivers adjacent to the field area, pumping or irrigation in close proximity to the observation well, tidal effects, barometric pressure, changes in overburden, etc. Noise from these sources may affect results in a variety of ways (Spane and Mackley, 2011). A disadvantage of hydraulic tomography using constant-rate pumping tests is that the signal associated with hydraulic tomography may not be easily distinguishable from these noises and trends.

Oscillatory hydraulic tomography is a subsurface imaging method that employs a tomographic analysis of oscillatory signals. In oscillatory signal tests, a periodic pressure signal can be imposed at one or more stimulation points, and the transmitted effects of this signal are recorded at monitoring wells. The idea of harmonic testing was first proposed in the petroleum literature by Kuo (1972) as an extension to pulse testing (Johnson et al., 1966; McKinley et al., 1968). More recent publications on reservoir characterization using harmonic tests include Fokker et al. (2012), Fokker and Verga (2011), and Ahn and Horne (2011). Oscillatory

* Corresponding author. Tel.: +1 650 724 3313.
E-mail address: taniab@stanford.edu (T. Bakhos).

http://dx.doi.org/10.1016/j.jhydrol.2014.01.007
0022-1694 © 2014 The Authors. Published by Elsevier B.V. Open access under CC BY-NC-ND license.

aquifer tests have similarly been used to estimate aquifer hydraulic parameters (Engard et al., 2005; Wachter et al., 2008; Becker and Guiltinan, 2010).

Oscillatory pumping tests have several advantages over traditional pumping tests including (1) a reduction in the cost of disposing of contaminated water because there is no net extraction or injection into the aquifer, (2) a reduced computational cost through use of a steady-periodic model and (3) an ability to distinguish the signal from the background noise. Disadvantages of oscillatory pumping tests may include (1) the need for potentially different field equipment to generate a periodic stimulation and (2) the amplitude of signals at the observation locations may be much smaller than those of signals generated by constant-rate pumping.

As a modification to oscillatory pumping test analysis, multi-frequency oscillatory hydraulic imaging was proposed by Cardiff et al. (2013) in which multiple signals of different frequencies are used as a stimulation to obtain information on the aquifer heterogeneity. The authors use a "steady-periodic" model formulation to analyze the head responses to the stimulation, which allows for a reduced computational cost in numerically solving the fully-transient model. This formulation assumes that the signal has reached a steady periodic state and assumes that the initial transient effects are negligible. An analysis of when this assumption can accurately be made is an important question that, to the best of our knowledge, has not yet been addressed. Black and Kipp Jr (1981) first introduced an analytic solution for the steady-periodic response of the signal to a line-source oscillatory stimulation for a homogeneous isotropic aquifer that is effectively laterally unbounded. This approach provided an estimate of the hydraulic diffusivity using the ratio of the amplitude or phase shift from two observations wells. Rasmussen et al. (2003) derived the leaky and partially penetrating analytic solution for transmissivity and storativity in a confined aquifer. They also provide expressions for the transient solution that decays with time.

We use the analytic expressions to show that the duration of the initial transient (i.e. number of periods required for the signal to achieve a steady-periodic response) is a function of a non-dimensional quantity. The non-dimensional expression depends on the following physical parameters: the frequency of oscillations, the radial distance from the source, and the hydraulic diffusivity. We extend the analysis to more general heterogeneous aquifers and derive bounds for the time required for the signal to reach a steady-periodic response.

The existence of signal processing routines for signal extraction and denoising for oscillatory signals was briefly discussed in Cardiff et al. (2013). To denoise an oscillatory signal, methods such as the discrete Fourier transform (Renner and Messar, 2006; Hollaender et al., 2002) and ordinary least squares (Rasmussen et al., 2003; Toll and Rasmussen, 2007) are commonly and successfully used. We assume the frequency of oscillations is known and demonstrate the effectiveness of ordinary least squares in recovering the signal in the presence of common sources of noise. We quantify the uncertainties in the estimates and show that the errors in estimating the components (phase and amplitude) of a signal decay with time. Using regression for denoising and using the results of the covariance of the estimator, we present a joint inversion of storativity and transmissivity of a synthetic 2-D example.

The paper is organized as follows. In Section 2 we review the governing equations. In Section 3, we discuss denoising the signal under various types of noise, which is followed by a joint inversion of storativity and transmissivity in Section 4. In Section 5, we analyze the behavior of the initial transient and follow with concluding remarks in 6.

2. Governing equations

In this section, we review the governing equations. This closely follows the notation and presentation of Cardiff et al. (2013). Groundwater flow through a 2-D depth-averaged confined aquifer with horizontal confining layers for a domain Ω and boundary $\partial\Omega$ is described by the following equations,

$$S(x)\frac{\partial h(x,t)}{\partial t} - \nabla\cdot(T(x)\nabla h(x,t)) = q(x,t), \qquad x\in\Omega \tag{1}$$

$$h(x,t) = 0, \qquad x\in\partial\Omega_D \tag{2}$$

$$\nabla h(x,t)\cdot \mathrm{n} = 0, \qquad x\in\partial\Omega_N \tag{3}$$

where n is the normal vector, $x\in\mathbb{R}^2$ (L) denotes the position vector, h (L) represents the hydraulic head, $S(x)$ (–) represents the storativity and $T(x)$ (L^2/T) represents the transmissivity. Ω_D and Ω_N refer to Dirichlet (constant head) and Neumann boundary conditions (constant flux) respectively.

Using Euler's formula, we represent the oscillator as an exponential function. For the case of one source at position x_s oscillating at a fixed frequency ω (radians/T), $q(x,t)$ is given by

$$q(x,t) = Q_0\delta(x-x_s)e^{i\omega t} \tag{4}$$

Because the solution is linear in time, the signal (after some initial time has elapsed) achieves a steady-periodic response and can be represented as,

$$h(x,t) = \Phi(x)e^{i\omega t} \tag{5}$$

where $\Phi(x)$, known as the phasor, carries information about the amplitude and phase of the signal. Plugging these definitions into (1) results in the more computationally efficient form,

$$i\omega S(x)\Phi(x) - \nabla\cdot(T(x)\nabla\Phi(x)) = Q_0\delta(x-x_s), \qquad x\in\Omega \tag{6}$$

$$\Phi(x) = 0, \qquad x\in\partial\Omega_D \tag{7}$$

$$\nabla\Phi(x)\cdot\mathrm{n} = 0, \qquad x\in\partial\Omega_N \tag{8}$$

The hydraulic head is given by (5) once Φ is known. Note that the steady-periodic formulation, i.e. Eqs. (6)–(8), only holds if we are able to neglect the initial transient.

3. Signal denoising

In this section, we will assume that the effects of the transient can be neglected and that the solution to the groundwater equations is a sinusoid of known frequency. Even though the solution is a sinusoid of known frequency, in practice, the measurement signals are corrupted by noise. In this section, we address how to recover the signal from a set of noisy measurements. We demonstrate the effectiveness of linear regression on four common types of noise: white noise, white noise with a jump in the signal, white noise with a linear drift and correlated noise, and quantify the errors in the estimates. This analysis hinges on the fact that the frequency is known however if the frequency is unknown, one can extract the frequency of the sinusoid by using the discrete Fourier transform and then proceed with this analysis.

Consider the measurement time series at a given point,

$$\Phi(\bar{x},t_i) = \beta_1\cos(\omega t_i) + \beta_2\sin(\omega t_i) + \epsilon(t_i) \tag{9}$$

where $\epsilon(t_i)$ is the residual or error term. We assume ϵ has zero mean. If ϵ has known mean μ, it can be detrended by subtracting it from (9). If μ is not known, it will be shown that the following analysis holds true provided the time between measurements is small enough. Rewrite Φ as

Download English Version:

https://daneshyari.com/en/article/6413294

Download Persian Version:

https://daneshyari.com/article/6413294

Daneshyari.com