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Improved predictions of saturated and unsaturated zone drawdowns in a heterogeneous unconfined aquifer via transient hydraulic tomography: Laboratory sandbox experiments

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S U M M A R Y

Interpretation of pumping tests in unconfined aquifers has largely been based on analytical solutions that disregard aquifer heterogeneity. In this study, we investigate whether the prediction of drawdown responses in a heterogeneous unconfined aquifer and the unsaturated zone above it with a variably saturated groundwater flow model can be improved by including information on hydraulic conductivity (K) and specific storage (S_s) from transient hydraulic tomography (THT). We also investigate whether these predictions are affected by the use of unsaturated flow parameters estimated through laboratory hanging column experiments or calibration of in situ drainage curves. To investigate these issues, we designed and conducted laboratory sandbox experiments to characterize the saturated and unsaturated properties of a heterogeneous unconfined aquifer. Specifically, we conducted pumping tests under fully saturated conditions and interpreted the drawdown responses by treating the medium to be either homogeneous or heterogeneous. We then conducted another pumping test and allowed the water table to drop, similar to a pumping test in an unconfined aquifer. Simulations conducted using a variably saturated flow model revealed: (1) homogeneous parameters in the saturated and unsaturated zones have a difficult time predicting the responses of the heterogeneous unconfined aquifer; (2) heterogeneous saturated hydraulic parameter distributions obtained via THT yielded significantly improved drawdown predictions in the saturated zone of the unconfined aquifer; and (3) considering heterogeneity of unsaturated zone parameters produced a minor improvement in predictions in the unsaturated zone, but not the saturated zone. These results seem to support the finding by Mao et al. (2011) that spatial variability in the unsaturated zone plays a minor role in the formation of the S-shape drawdown-time curve observed during pumping in an unconfined aquifer.

1. Introduction

In recent decades, the topic of flow to wells during pumping in unconfined aquifers has become an issue of great interest and great debate. The need to better understand and interpret the observations from these tests has led to the development of various analytical solutions (e.g., Boulton, 1954, 1963; Dagan, 1967; Kroszynski and Dagan, 1975; Streltsova, 1973; Neuman, 1972, 1974; Moench, 1997; Mathias and Butler, 2006). Mishra and Neuman (2010) provided a comprehensive review of these solutions and offered their perspectives on the advancement of the theoretical development of unconfined aquifer analysis. Mishra and Neuman (2010) also presented an approximate analytical solution for flow to a partially penetrating well in a compressible unconfined aquifer that infers saturated and unsaturated hydraulic properties from drawdowns recorded in the saturated and/or unsaturated zone. More recently, Mishra and Neuman (2011) extended the solution of Mishra and Neuman (2010) to consider a finite diameter pumping well with storage and the effects of delayed piezometer response. Mishra and Neuman's (2010, 2011) solutions are an extension of the solution developed by Tartakovsky and Neuman (2007) and adds: (i) a more flexible representation of unsaturated constitutive properties; and (ii) a finite thickness for the unsaturated zone. Mishra and Neuman (2010) used their type curve approach in conjunction with the Model-Independent Parameter Estimation and Uncertainty Analysis Model (PEST) (Doherty, 1994) to simultaneously analyze seven observed drawdown records from a pumping test conducted at the Cape Cod site by Moench et al. (2001). The analysis yielded comparable estimates of hydraulic conductivity (K) and specific storage (S_s) and somewhat higher values of specific yield (S_y) when compared to those obtained by Moench et al. (2001) and Tartakovsky and Neuman (2007). Their estimates of the van Genuchten–Mualem parameters were also found to be

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comparable to laboratory estimates obtained for similar materials in the area. Despite the usefulness of Mishra and Neuman's (2010, 2011) solutions, they are linearized solutions that treat the medium to be homogeneous and unbounded media and thus cannot address the issue of heterogeneity, which is the rule rather than the exception.

Recently, the homogeneity assumption required by analytical solutions for heterogeneous saturated aquifers have come into question by Wu et al. (2005) and Wen et al. (2010). In particular, Wu et al. (2005) used random Gaussian fields (of transmissivity and storativity) to demonstrate that parameter estimates made using the Theis (1935) solution varied throughout the duration of the pumping test. Transmissivity estimates approached the geometric mean and storativity estimates were dominated by the material between the pumping well and the observation point. It is reasonable to expect similar limitations for analytical solutions used to estimate parameters from unconfined pumping tests. Similar results were reported by Wen et al. (2010) for field aquifer tests with a large number of observation wells.

To date, only a limited number of investigations have explicitly examined the effect of heterogeneity on pumping tests performed in unconfined aquifers (e.g., Bunn et al., 2010; Mao et al., 2011). For example, using multiple realizations of heterogeneous fields, Bunn et al. (2010) examined the connection between K heterogeneity and the capillary fringe extension phenomenon observed during a pumping test conducted by Bevan et al. (2005) at the Borden site in Canada. The ensemble mean hydraulic heads were able to reproduce the field observations quite well, however, these simulations were unable to reproduce the capillary fringe extension observed in the field data.

More recently, Mao et al. (2011) utilized the stochastic moment approach to better understand the role of heterogeneity in the development of the S-shaped drawdown curves and a cross-correlation analysis to show that drawdowns at locations in a heterogeneous unconfined aquifer are mainly affected by local heterogeneity near the pumping and observation wells. Mao et al. (2011) also critically examined the sensitivity of the S-shaped curve to the spatial variability of hydraulic parameters and concluded that it is most sensitive to hydraulic conductivity (K), specific storage (S_s) and saturated water content (θ_s) and found that it was insensitive to the variability of unsaturated hydraulic parameters.

Mapping of K heterogeneity in unconfined aquifers was recently reported by Cardiff et al. (2009) under steady-state conditions. These authors analyzed multiple drawdown data collected from fully-screened wells completed in an unconfined aquifer located at the Boise Hydrogeophysical Research Site to obtain depth-averaged K distributions through their hydraulic tomography algorithm. Various inverse methods have been developed for hydraulic tomography, which utilize pumping test data simultaneously or sequentially (e.g., Gottlieb and Dietrich, 1995; Yeh and Liu, 2000; Bohling et al., 2002; Brauchler et al., 2003, 2011; Zhu and Yeh, 2005, 2006; Li et al., 2005, 2007; Fienen et al., 2008; Castanaga and Bellin, 2009; Xiang et al., 2009; Liu and Kitanidis, 2011; Cardiff and Barrash, 2011). But to our knowledge, hydraulic tomography algorithms that can interpret the transient drawdown records from a heterogeneous, unconfined aquifer that rigorously considers the unsaturated zone does not exist except for the one developed by Zhu et al. (2011). One reason for this is that pumping in unconfined aquifers induces flow regimes in both the saturated and unsaturated zones. This demands the use of a variably saturated flow equation that considers heterogeneity for the interpretation of drawdown responses in an unconfined aquifer. Inverse modeling of flow through variably saturated and heterogeneous media is a very difficult task (Yeh and Zhang, 1996; Zhang and Yeh, 1997; Li and Yeh, 1999; Hughson and Yeh, 1998, 2000).

In this study, we investigate whether the prediction of drawdown responses in a heterogeneous unconfined aquifer and the unsaturated zone above it with a variably saturated groundwater flow model can be improved by including information on hydraulic conductivity (K) and specific storage (S_s) from transient hydraulic tomography (THT). We also investigate whether these predictions are affected by the use of unsaturated flow parameters estimated through laboratory hanging column experiments or calibration of in situ drainage curves. To investigate these issues, we designed an intermediate-scale laboratory sandbox containing a heterogeneous unconfined aquifer that was instrumented with pressure transducers, tensiometers, and water content sensors. A number of pumping tests are performed while the tank was fully saturated. These pumping tests are then used to estimate both homogeneous and heterogeneous K and S_s distributions. Parameters of the moisture release curves of different material types in the sandbox are measured using hanging water column experiments and in situ by fitting the van Genuchten (1980) model.

We next conducted another pumping test in which we allow the water table to fall, while the drawdown in the sandbox is monitored at multiple locations in the saturated zone with pressure transducers. Concurrently, we monitored the unsaturated zone with tensiometers (equipped with pressure transducers) and water content sensors. After this, we modeled the pumping test using MMOC3 (Yeh et al., 1993), a 3-D variably saturated flow and transport model to evaluate the ability of different homogeneous and heterogeneous representations of the sandbox aquifer in both the saturated and unsaturated zones to reproduce the observed drawdown responses. By comparing various idealizations of saturated and unsaturated zone parameters, we were able to find out what parameters have the greatest impacts on making accurate predictions of responses in the unsaturated and saturated zones.

2. Experimental setup

2.1. Sandbox design and instrumentation

A synthetic heterogeneous unconfined aquifer was constructed in a vertical, laboratory sandbox to investigate how the saturated and unsaturated zones respond to a pumping test that results in drainage. The sandbox was 244 cm in length, 122 cm in height, and had a thickness of 9.4 cm. A glass plate covers the front of the sandbox and a stainless steel plate covers the back. A total of one hundred four ports were drilled into the stainless plate to allow the sandbox to be instrumented with pressure transducers, tensiometers, and water content sensors.

Fifty-eight of these ports were used for the installation of fully penetrating horizontal wells (1.4 cm in diameter). In the vertical direction, these wells behave as partially penetrating wells. Each well was constructed by drilling 14 0.5-cm diameter holes along a section of brass tubing. The holes were then covered with a stainless steel mesh that was bonded to the tubing with corrosion resistant epoxy. These wells, which penetrate the thickness of the synthetic aquifer were installed after the packing of the sandbox aquifer. Additionally, 47 of these wells contain 0–2 psig pressure transducers (Model S35) from BHL Instruments. Eleven wells did not contain pressure transducers, but were still able to be used for pumping purposes.

Twenty-two of the ports (located in the upper portion of the sandbox) were used for the installation of column tensiometers (CL-029B Flow Cell Tensiometer, Soil Measurement Systems) equipped with Microswitch pressure transducers. The remaining 24 ports (also located in the upper portion of the sandbox) were instrumented with EC5 water content sensors (Decagon Devices Inc.). All sensors were connected to a National Instruments