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Effects of hydraulic conductivity heterogeneity on vadose zone response to pumping in an unconfined aquifer

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SUMMARY

It is of great importance to be able to properly simulate flow mechanisms within the vadose zone as they are controlling factors for solute transport to groundwater bodies. The highly detailed pumping test data set collected by Bevan et al. (2005) at the Borden aquifer provides a unique opportunity to investigate the controlling factors for fluid flow and moisture distribution in the vadose zone in response to pumping. The field results show capillary fringe thicknesses that increased with duration of pumping, and decreased with distance from the well. This increased thickness was persistent for the duration of the 7 day test. Previous numerical analysis of the pumping test has been able to replicate the observed moisture contents at discrete time intervals (Moench, 2008), but the physical mechanisms controlling the moisture content observations are poorly understood.

Hydraulic conductivity heterogeneity has been proposed as a potential mechanism for the capillary fringe extension observed in the field. Using stochastic hydraulic conductivity fields, moisture content distributions observed during the Bevan et al. (2005) pumping test were simulated using a variably saturated numerical model. A Monte Carlo analysis was performed and ensemble results are presented. The ensemble mean hydraulic head drawdown was an adequate match to the field data, although there was a small but consistent over prediction of drawdown. The ensemble mean thickness of the capillary fringe was not significantly different from the result of a homogeneous simulation, and did not replicate the increasing thickness observed in the field. The ensemble mean capillary fringe extension was not found to be dependent upon distance from the pumping well or duration of pumping. Zones of perched water were formed in many of the heterogeneous realizations; however, neutron probe data collected during the field experiment does not support the presence of these perched zones.

1. Introduction

While commonly used, pumping tests in unconfined aquifers have historically been the source of debate in the literature. Complications in obtaining observational data and modeling of the partially saturated flow above the water table have limited our understanding of the drainage processes occurring during pumping. In 2001, a pumping test conducted at the Canadian Forces Base (CFB) Borden Site by Bevan et al. (2005) (referred to as the Borden test in this paper) once again highlighted the complexity of the drainage from the vadose zone during pumping. The 7 day test was intensely monitored, and included a series of moisture profiles taken at six different radial distances from the pumping well. The results of the test (Bevan, 2002, and Bevan et al., 2005) have been cited as a "benchmark" for aquifer analysis (Moench, 2008). This test was significantly longer than the Nwankwor et al. (1992) test and resulted in the observation of excess storage within the capillary fringe which persisted to the end of the test at 7 days. The excess storage was in the form of an extended capillary fringe (i.e. a tension-saturated thickness during pumping which is thicker than the observed static thickness prior to pumping). The extension of the capillary fringe was found to be a function of duration of pumping and distance from the pumping well (Bevan et al., 2005). During the Borden test, the shape of the moisture profile from full to residual saturation (transition zone) remained relatively constant; the moisture content profile through the transition zone essentially translated downwards during pumping-induced drainage (Bevan et al., 2005).

The analytical solutions of Boulton (1954, 1963), and Neuman (1972, 1974) have been the benchmarks of unconfined pumping test analysis, and are still commonly used in practice. These analytical solutions implicitly incorporate the contribution of the vadose zone through a boundary condition at the water table. Moench (1995) combined the analytical methods of Neuman (1972, 1974) with the exponential drainage condition of Boulton (1963) to

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obtain a new analytical solution that accounted for both vertical and horizontal flow below the water table. It is noted that in these analytical solutions, the water table boundary condition implies that only vertical flow occurs above the water table. The Borden test was analyzed using these three analytical methods by Endres et al. (2007). In these simulations, the Borden aquifer was treated as homogeneous and mildly anisotropic. Good predictions of the hydraulic head drawdowns in the monitored piezoemeters were achieved with all of the models. Endres et al. (2007) considered vadose zone response by comparing analytical specific yield estimates with laboratory derived values. While the modified Bolton solution was able to approximate the laboratory derived specific yield, none of the analytical solutions were able to predict the observed undrained storage in the vadose zone. Moench (2008) continued to test the applicability of analytical analyses of the Borden test using the Mathias and Butler (2006) semi-analytical solution. This solution explicitly accounts for flow above the water table, yet the results generated by the solution were similar to the results achieved by Endres et al. (2007).

While implicit inclusion of the drainage contribution is an accepted analytical technique, field and numerical studies which explicitly include the vadose zone support a more physically based representation of pumping-induced drainage. Nwankwor et al. (1992) measured soil moisture content and pressure heads above the water table during a pumping test at CFB Borden. Their analysis found that the specific yield value derived from a volume balance method was much greater than that estimated from implicit analytical solutions. This discrepancy was attributed to the delayed drainage phenomenon (Nwankwor et al., 1992). Akindunni and Gillham (1992) simulated this test using a variably saturated numerical model, and verified the ability of numerical methods to capture the flow physics occurring above the water table observed by Nwankwor et al. (1992). Using numerical experiments Narasimhan and Zhu (1993) concluded that drainage from the unsaturated zone was a complex function of time and required an explicit inclusion of flow in the unsaturated zone that would be best approximated using numerical models.

Moench (2008) used the numerical model VS2D (Lappala et al., 1987) to simulate the Borden test. Although VS2D numerically represents both horizontal and vertical flow above the water table and is similar to the numerical model used by Akindunni and Gillham (1992), the simulations by Moench (2008) underestimate the amount of undrained storage observed during the Borden test. A better approximation of the vadose zone observations was achieved by defining the saturation–relative conductivity relationship using a separate set of parameters from the pressure–saturation relationship (Moench, 2008). By defining a relative conductivity that decreased rapidly as the aquifer drained, Moench (2008) was able to calibrate the model to match the Borden test observations for a given time. Independent calibration of the model to three observation times resulted in three different saturation–relative conductivity relationships. These results suggest that the mechanism resulting in the observed undrained storage must be both persistent for the duration of the test and dependent on the flow rate in the aquifer (Moench, 2008).

Moench (2008) suggested a number of physical mechanisms for the Borden test observations including reduction of the hydraulic conductivity due to entrapped air resulting from seasonal fluctuations in the water table, increased bulk density (and reduced pore size) due to compaction of the unconsolidated soil, and heterogeneity of the hydraulic conductivity, resulting in an enhanced value of anisotropy, reducing the vertical flux in the capillary fringe. It is the aim of the current study to assess the impact of heterogeneity in the Borden aquifer on the moisture content observations observed by Bevan et al. (2005).

Although the Borden aquifer is only mildly heterogeneous, the effects of heterogeneity in the unsaturated zone are magnified. Theoretical analysis (Yeh et al., 1985a,b,c; Mantoglou and Gelhar, 1987; Green and Freyberg, 1995; Li and Yeh, 1998; Jacobs and Gelhar, 2005) and experimental observations (Stephens and Heermann, 1988; Yeh and Harvey, 1990. Silliman et al., 2002; Wildenschild and Jensen, 1999; Glass et al., 2005) have shown that heterogeneity can have a controlling effect on the variation in moisture content and pressure head above the water table under a natural gradient. Our numerical simulation of this heterogeneity was designed to determine whether the inclusion of small scale heterogeneities in pumping test modeling could provide a better approximation of the moisture content distributions observed by Bevan et al. (2005) in the Borden aquifer. Our inclusion of heterogeneity in the numerical model will help to reduce the uncertainty in our numerical description of the vadose zone at the Borden aquifer, furthering our understanding of the mechanisms at play during pumping-induced drainage in unconfined aquifers. The Borden aquifer has been has been well characterized through numerous field studies, and the heterogeneity in saturated hydraulic conductivity at the site is well documented. MacFarlane et al. (1983) noted the variation of grain size from medium sand to fine sand and silt on the core scale, but asserted that the aquifer is homogeneous on the scale of a pumping test. As part of a natural gradient experiment, Sudicky (1986) performed permeameter measurements on 1279 samples from this aquifer resulting in a lognormal conductivity distribution with a mean of 7×10^{-5} m/s and a variance of 0.38. The results of the natural gradient experiment in the Borden aquifer show the effects of the elongated bedding which impedes flow in the vertical direction (Freyberg, 1986, and MacKay et al., 1986). A mild degree of anisotropy has been typically used to represent this stratified and cross-bedded aquifer (see Akindunni and Gillham, 1992; Endres et al., 2007; Moench, 2008).

In this study the Borden aquifer was viewed as heterogeneous and geostatistically characterized using the results of Sudicky (1986). A homogeneous model assuming a mild degree of hydraulic conductivity anisotropy is used for comparison. The effect of heterogeneity on the pumping test was determined using a Monte Carlo analysis. The impact of pumping stress on the compaction of the aquifer and the likely impact of entrapped air are also addressed in a qualitative manner. The data set presented in Bevan et al. (2005) provides an unprecedented glimpse into the field-scale response of the vadose zone to pumping. Narasimhan (2007) has stated that the Borden test "provides motivation to examine the broader question of how best we may use available mathematical models and tools to characterize and quantify the behavior of aquifer systems". It is imperative that this data is viewed as an opportunity to link the unconfined aquifer response to pumping to a mechanistic process, thereby improving the understanding of the processes which most directly impact water flow. An improved understanding of the physics of the system will facilitate the generation of more meaningful mathematical representations of unconfined pumping tests.

2. Field data

The data set discussed in this study was gathered during a 7 day pumping test conducted at CFB Borden, Ontario in August 2001. Full details about this test and its results can be found in Bevan (2002) and Bevan et al. (2005). For this paper we have attempted to simulate the Borden test using a heterogeneous description of the saturated hydraulic conductivity. The Borden test was conducted in a topographically flat area with a uniform aquifer thickness of 9 m. Prior to the commencement of the pumping test, the