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Field observation of the response to pumping and recovery in the water table region of an unconfined aquifer

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SUMMARY

A 24-h pumping test was conducted in the shallow water table portion of an unconfined aquifer located at Canadian Forces Base Borden near Alliston, Ontario, Canada. This test was designed to monitor the dynamic nature of the vertical gradients that form within the zone of tension saturation above the water table during pumping and recovery. During the test, pressure head was monitored throughout the saturated zone, both above (tensiometers) and below (piezometers) the water table; soil water content was monitored using both neutron moisture probes and time domain reflectometry (TDR). Following pumping, recovery was monitored in the same manner as the pumping portion of the test. The hydraulic head drawdown observed above the water table in the tension saturated zone during pumping and recovery was very similar to the drawdown observed below the water table. Vertical gradients throughout the saturated zone appeared to be uniform and low, and did not change significantly in the transition across the water table. The magnitude of the vertical gradients peaked early in the test, and subsequently decreased, with the reduction being more significant at greater radial distances from the pumping well. Neutron measurements indicate that only a minor degree of drainage occurred within the measurement interval for the duration of the test, a result of the low magnitude of drawdown generated during pumping and influence of hysteresis on the moisture profile. Although drainage was negligible from within the tension saturated zone during pumping, the hydraulic head drawdown below the water table displayed reduced rates of drawdown during the intermediate period of the test. TDR data was only collected during recovery; however, the data set displays hysteretic behavior in the pressure–saturation profiles, with all profiles plotting on scanning curves. Based on these observations it appears that a conceptual model in which vertical gradients below the water table are of the same order of magnitude as those within the capillary fringe is appropriate for the analysis of vadose zone response to pumping.

1. Introduction

Pumping tests in unconfined aquifers have a long history of use in groundwater research and practice. While pumping induced hydraulic head drawdown is frequently used in practice to determine aquifer properties, the drainage processes and vadose zone response associated with this drawdown are still a source of uncertainty. Although new technologies have advanced our ability to observe the aquifer response above the water table, there remain a limited number of field experiments targeted at broadening our understanding of the transient response to pumping in the shallow zones of unconfined aquifers. The pumping of unconfined aquifers is typically carried out in a dynamic manner to respond to water supply demand, and to capture and control groundwater and soil contamination. Understanding of the development of hydraulic gradients in this environment is essential to furthering the understanding and accuracy of capture zones and remediation planning.

Pumping tests in unconfined aquifers differ from a confined aquifer test in that the aquifer is dewatered. The resulting hydraulic head drawdown curve, for observation points near the pumping well, consists of three stages when presented in a log–log format. These three stages are classically interpreted in the following manner. The first stage typically follows the Theis (1935) equation and represents the release of water from elastic storage. The second stage of the test is characterized by a reduced rate of drawdown due to dewatering of the aquifer material above the water table. The third segment of the test follows a second Theis (1935) curve that is controlled by the specific yield of the aquifer (Batu, 1998). While this three part curve can be approximated both analytically and numerically, the drainage and storage release processes which control its shape are still a source of debate.

Nwankwor et al. (1992) undertook a detailed pumping test, making use of tensiometers and gamma moisture devices to

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observe the drainage processes in the unconfined sandy aquifer at Canadian Forces Base (CFB) Borden, Ontario. The results of the Nwankwor et al. (1992) test supported the concept of a delayed yield phenomenon. Specifically, during the first phase of pumping in which drawdown was found to increase rapidly, vertical gradients were found to increase monotonically. These downward gradients corresponded to an increase in storage above the water table as a result of the pressure–saturation relationship for the sand. Early in the test the magnitude of the vertical gradients peaked, and the excess storage was released through downward drainage. This drainage resulted in a progressive decrease in the magnitude of the vertical gradients. As this additional source of water reached the water table, drawdown rates were temporarily decreased. This test provided physical data which supported the delayed yield concept and its effect on the shape of the curve typically observed in unconfined pumping tests. Numerical experiments by Narasimhan and Zhu (1993) supported the concept of delayed drainage from the unsaturated zone. Subsequent analysis of an unconfined pumping test in the glacial outwash sediment of Cape Cod by Moench et al. (2001), highlighted the need to include all physical processes affecting drawdown, including delayed yield, in the analysis of unconfined pumping tests.

The study of the response of unconfined aquifers was further expanded by the Bevan et al. (2005) pumping test, which is referred to as the Bevan test in this work. This test, also conducted at the CFB Borden site, expanded on the work of the Nwankwor et al. (1992) test with a 7-day pumping test that included observations of hydraulic head and moisture content. In addition, recovery was monitored for a period of 5 days following pumping. The hydraulic head drawdown and vertical gradients below the water table were qualitatively similar to those observed by Nwankwor et al. (1992), with gradients that increased at early time and decreased with pumping duration. However, the Bevan et al. (2005) data shows vertical gradients below the water table that decrease to non-zero values, with gradients that continue to the end of pumping at 7 days. Although the Bevan et al. (2005) data set does not include hydraulic head measurements from above the water table, very detailed moisture content data was collected using a neutron moisture probe. The results of the test showed a differential drawdown that occurred between the top of the tension saturated zone and the water table. The differential drawdown resulted in an extension of the tension saturated zone where the degree of extension appeared to be a function of distance from the pumping well, and pumping duration. This extension was found to persist to the end of pumping at 7 days (Bevan et al., 2005), which is far longer than the duration of the delayed yield phenomenon reported by Nwankwor et al. (1992), as well as the time from the beginning of pumping to the peak in vertical gradients reported by Bevan et al. (2005).

Following the work of Bevan et al. (2005), attempts have been made to make use of the data collected during the Bevan test in order to broaden our understanding of the response to pumping in unconfined aquifers. Endres et al. (2007) investigated the ability of analytical solutions to capture the test response and found that none of the boundary conditions used to simulate drainage from above the water table, including those which incorporated delayed yield, could replicate the observed bulk vadose zone response to pumping. Moench (2008) investigated the test using both semi-analytical and numerical techniques. This analysis provided a great deal of insight into how best to incorporate the vadose zone flux in a semi-analytical framework. However, neither a semi-analytical nor a numerical approach was able to capture the vadose zone response observed during the Bevan test. Moench (2008) was able to provide a closer approximation of the Bevan et al. (2005) results by adding an additional pressure–saturation parameter, and dividing the test into separate time blocks, each with a unique parameter set. Through this work, Moench (2008) suggested that the nature of the heterogeneity derived hydraulic conductivity anisotropy at the site may be a factor in the evolution of the moisture profiles which evolved over the course of the Bevan test.

In an attempt to improve the site conceptual model of the Bevan test, Bunn et al. (2010) constructed a heterogeneous hydraulic conductivity field based on the geostatistical data for the Borden aquifer presented by Sudicky (1986). This field was used to conduct numerical simulations of the Bevan pumping test, and a Monte Carlo analysis was performed on the results. Although the ensemble mean of the heterogeneous simulation provided a better fit to the hydraulic head drawdowns in early and intermediate times, there was no significant difference between the homogeneous model and the ensemble mean moisture content results. The work of Bunn et al. (2010) provided a numerical simulation which was closer to actual field conditions than previous simulation attempts; however, the Monte Carlo results did not support heterogeneity as the primary cause of the extension observed during the Bevan test.

The current study expands on the long history of pumping in the Borden aquifer by presenting the results of a 24-h pumping test conducted in the shallow water table portion of the aquifer. This test differs from the previous tests conducted at CFB Borden in that it was completed in a different location with a lower surface elevation, and was conducted during a wet season in which the regional water table was near its seasonal high, having undergone a gradual rise. These two factors resulted in a shallow water table, facilitating the installation of observation points within the capillary fringe. As the water table was very gradually rising prior to pumping, the background moisture profile resembled the laboratory derived imbibition curve. As the water table was drawn down though the course of the pumping test the moisture profile shifted to an intermediary curve between imbibition and drainage, providing an opportunity to observe the impact of hysteresis on the unconfined response to pumping. The pumping rate imposed during this test, and the resulting drawdowns were significantly lower than previous tests. Observations were made more frequently during the early phases of pumping and recovery compared to earlier tests. The implications of these differences will be discussed in further detail below.

The main objective of this test was to observe the transient nature of the vertical gradients within the capillary fringe, and in the transition from saturated to tension saturated conditions. The data gathered allow for an investigation into the validity of some of the assumptions required to analyze the Bevan test. As no pressure head data was collected above the water table during the Bevan test, the predictions of water table positions, and hydraulic head distributions above the water table made in the analysis of that test (Bevan et al., 2005; Endres et al., 2007; Moench, 2008; Bunn et al., 2010) rely on the assumption of low vertical gradients that are of similar magnitude to those observed throughout the saturated zone, which do not decrease to no flow conditions at any time during the test. The pumping test presented herein includes pressure head measurements from within the tension saturated zone, above the water table, to verify this assumption. Saturation data were collected during this test using both a neutron moisture probe and time domain reflectometry (TDR). The results of this study provide new observations of the development of the vertical gradients, and the drainage processes throughout the entire saturated zone including the tension saturated zone in relation to both the rates of drawdown, and the flow field development.

2. Site description

The pumping test was conducted in the unconfined aquifer at CFB Borden, Ontario. Numerous field experiments conducted at the site have provided a detailed description of the hydrogeologic