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A field scale study of pumping-induced drainage and recovery in an unconfined aquifer

Michael J. Bevan[a], Anthony L. Endres[b,*], David L. Rudolph[b], Gary Parkin[c]

[a]*Formerly Department of Earth Sciences, University of Waterloo, Waterloo, Ontario; presently Komex International, Calgary, Alta.*
[b]*Department of Earth Sciences, University of Waterloo, Waterloo, Ont., Canada N2L 3G1*
[d]*Land Resource Science, University of Guelph, Guelph, Ont., Canada*

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Abstract

An aquifer test involving seven days of pumping and five days of recovery was performed in the unconfined aquifer at Canadian Forces Base Borden in Ontario, Canada. Hydraulic head levels were intensively monitored in eleven observation wells, and moisture content profiles were frequently logged using a neutron moisture probe at six different radial distances from the pumping well. Capillary fringe thickness variations were inferred by comparing these hydraulic and moisture content measurements.

Allowing for the effects of lithologic variations, the response of the moisture content profile is predominately characterized by a downward translation during pumping-induced drainage. Our observations indicate that there is minimal excess storage above the capillary fringe at late times. The capillary fringe extended significantly with pumping in comparison to its static thickness; this extension progressively increased during the entire test. The capillary fringe extension decreased with increasing radial distance and was inferred to have eventually extended out to between 20 and 25 m. This extension represented a significant volume of excess capillary fringe storage that persisted into late times. A direct relationship between the vertical gradients below the water table and the excess capillary fringe storage is not apparent from these experimental data.

Analogous to the pumping test observations, the response of the moisture content profile during recovery is essentially an upward translation. While the hydraulic head levels recovered nearly to their pre-pumping elevations, the moisture content profiles stabilized approximately 0.20 m below their pre-pumping positions. This recovery differential leads to a capillary fringe compression that converted excess storage during pumping into storage deficit during recovery. In contrast to the significant radial variation of the capillary fringe extension during pumping, the capillary fringe compression is relatively uniform out to at least 15 m during the late recovery stage. The recovery deficit and entrapped residual air observed below the upward translating transition zone are strong indications that significant hysteretic processes are occurring at the field scale.
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Keywords: Aquifer test; Unconfined aquifer; Drainage; Recovery; Vadose zone; Moisture profile

* Corresponding author. Tel.: +1 519 888 4567x3552; fax: +1 519 746 7484.
E-mail address: alendres@sciborg.uwaterloo.ca (A.L. Endres).

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1. Introduction

Pumping and recovery tests are commonly used to determine the properties of unconfined aquifers (i.e. transmissivity, storativity and specific yield). The analyses of the data obtained from these aquifer tests are based on mathematical models for unconfined aquifer behavior. Because of the complexity of unconfined aquifer systems, these models contain approximations and assumptions that make their solutions more tractable. A number of authors (e.g., Neuman, 1979; Narasimhan and Zhu, 1993) have investigated the applicability of the assumptions. In almost all case, the conclusions of these studies are based on numerical modeling. While these studies are useful, additional insight can be derived from the interpretation of data collected during actual hydraulic testing of unconfined aquifers.

One critical parameter obtained from aquifer pumping test analyses is specific yield. Accurate values of this parameter are important to properly quantify the potentially extractable water volume from an unconfined aquifer; the main source of this water is drainage from above the declining water table. While it is possible to obtain reasonable estimates of specific yield (Moench, 1994), unrealistically low values of this parameter are often obtained in practice (Kruseman and de Ridder, 2000).

It has been proposed that poor specific yield estimates are a result of inadequately describing drainage phenomena in the analytical solutions used for pumping test analyses (Nwankwor et al., 1984; 1992). This problem is partially due to the fact that the drainage processes occurring during a pumping test in an unconfined aquifer are poorly understood. To improve the understanding of these processes at the field-scale, detailed observations of the relationship between transient hydraulic head and moisture content distribution during pumping tests are required.

Existing field-scale data on pumping-induced drainage are limited. Nwankwor et al. (1992) performed a 24-h pumping test in the Borden aquifer during which transient hydraulic head and moisture content data were acquired, concentrating on earlier time response. Hydraulic head data were obtained in both the saturated and unsaturated zones and provided information on the temporal behaviour of vertical hydraulic gradients. In-situ moisture content data were acquired using a gamma attenuation technique and gravimetric water content analyses performed on soil cores obtained during pumping. While these data provided useful information on pumping-induced drainage, the tests were of too short a duration to observe the longer-term relationships between drainage and hydraulic head drawdown.

Recovery tests also provide valuable aquifer information. Usually, the late-time hydraulic head data, when elastic storage effects have dissipated, are analyzed using the Theis recovery method (e.g. Kruseman and de Ridder, 2000). The early- and intermediate-time hydraulic head data during recovery are not commonly examined in detail. Further, the behavior of the moisture content profile at the field-scale during recovery and its relationship to hydraulic head below the water table during this process are not well understood. To date, observations of the moisture content profile during recovery have not been published. These observations are important for understanding the imbibition process and potential hysteretic effects during recovery.

Geophysical imaging techniques have recently been applied to monitoring aquifer tests (e.g. Endres et al., 2000; Bevan et al., 2003). In general, these methods respond to variations in subsurface water content and have the potential to provide independent information about the drainage and imbibition. If these measurements are to be incorporated with standard hydraulic head data in aquifer test analyses, it is necessary to establish the relationship between moisture content distribution and hydraulic response of aquifers during testing.

This study presents the results of an extensively monitored pumping and recovery test in the unconfined Borden aquifer. This test was designed to improve the understanding of the moisture content profile response and its relationship to hydraulic head measurements during both pumping and subsequent recovery. Our experimental design expanded on the previous work by Nwankwor et al. (1992) in a number of aspects. First, the pumping test was performed for a seven-day duration to observe the late-time aquifer response. Second, the water content profile and hydraulic head was observed for five days during recovery. Third, the moisture content profile was monitored at denser radial and vertical sampling

intervals in this experiment. While our observations support some concepts proposed by Nwankwor et al. (1992) regarding drainage during pumping, other aspects of observed aquifer behaviour differed significantly from those reported in that earlier work.

2. Site description

A well instrumented pumping test site at Canadian Forces Base Borden, near Barrie, Ontario was used to conduct the pumping and recovery test. This site has been the focus of other experiments concerning unconfined aquifer response to pumping (Nwankwor et al., 1984; 1992) and the geophysical imaging of this response by ground penetrating radar profiling (Endres et al., 2000; Bevan et al., 2003).

The unconfined aquifer is composed primarily of medium-grained sand of glacio-deltaic or glacio-fluvial origin. It can be locally heterogeneous due to lenses and beds of fine-, medium-, and coarse-grained sand (MacFarlane et al., 1983). A low degree of spatial variability in hydraulic conductivity exists among the discontinuous beds and lenses that are up to several meters in length (Sudicky, 1986). The aquifer is approximately 9 m thick; it is underlain by a clayey silt aquitard. At the time of the test in August 2001, the initial water table depth was 2.75 m, giving an initial saturated aquifer thickness of 6.25 m. Fig. 1 shows a schematic diagram of the pre-test (i.e. equilibrium) water content profile for this site based on the field observations of Nwankwor et al. (1992). The zone of residual water content (volumetric moisture content $\theta_w = 0.07$) extends downwards from the surface to 0.70 m above the water table; this level of water content is also referred to as specific retention and field capacity. The transition zone from residual water content to full saturation ($\theta_w = 0.37$) extends for approximately 0.40 m above a capillary fringe (i.e. zone of tension saturation) that has an average thickness of 0.30 m. This profile is similar to the profile predicted from laboratory measurements of the water content-pressure head relationship by Nwankwor (1984).

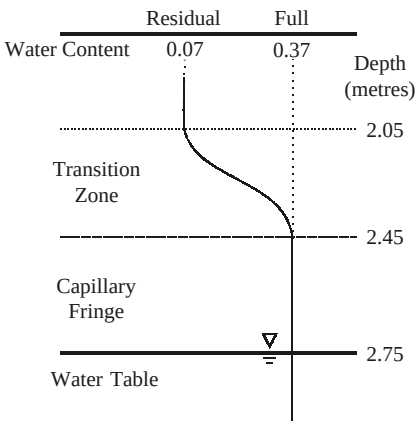

Fig. 1. Schematic diagram of the moisture content profile at the test site prior to the pumping and recovery test.

The pumping well at the site has a 0.13 m inner diameter (ID) with a stainless steel slotted telescopic screen over the bottom 3.65 m of the aquifer. Forty-two observation wells are distributed at various distances from the pumping well; most of these wells are screened over 0.35 m intervals at various depths within the aquifer. While all observation wells were monitored, this study will focus on four pairs of intensely monitored deep-shallow observation wells along a southward transect from the centrally located pumping well. These pairs are located at 1.5, 3, 5 and 15 m from the pumping well. These particular wells were selected because they provide vertical hydraulic gradient information below the water table in the proximity of newly installed moisture content instrumentation.

For this experiment, six neutron moisture probe access tubes were installed for monitoring the water content profile during pumping and recovery. These holes were drilled to depths of approximately 4 m and fitted with sealed 0.05 m ID PVC casings. The access tubes are located at six radial distances from the pumping well (1,3,5,10,15 and 20 m) along the southward transect of observation wells. Fig. 2a displays a plan view of the wells and access tubes; Fig. 2b shows a vertical cross-section along the southern transect.

3. Field methods

The pumping test was performed for 7 days at a constant discharge rate of 40 ± 1 l/mm; the subsequent recovery was monitored for 5 days. The pumping rate was verified at regular intervals by

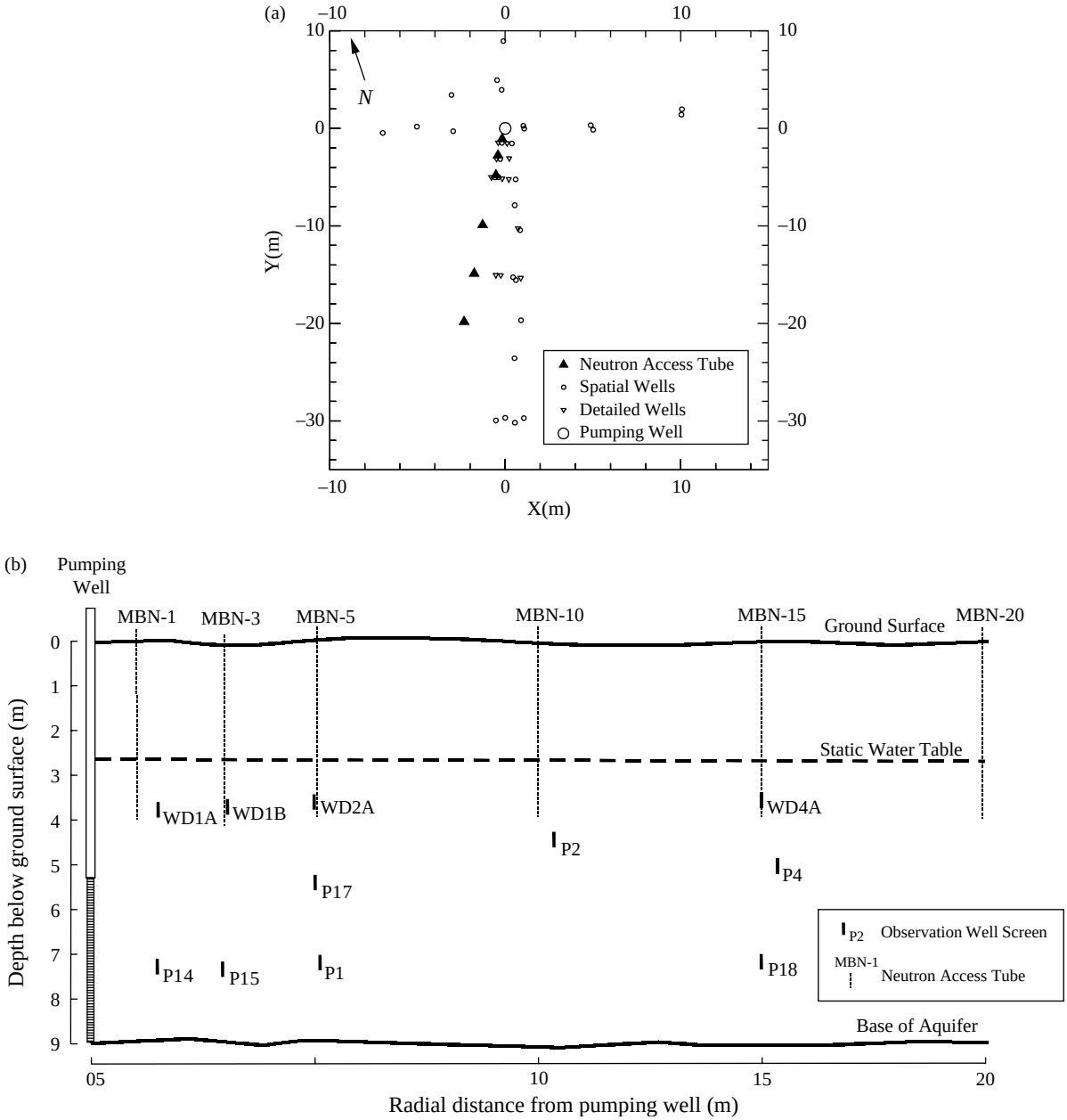

Fig. 2. (a) Plan view of CFB Borden pumping test site. (b) Cross section of the aquifer and instrumentation southward from the pumping well.

determining the time required to fill a container of known volume with water pumped from the well. To obtain detailed time-drawdown data, hydraulic head levels were measured in 11 observation wells along the southward transect using pressure transducers and a data logging system, providing water level drawdowns accurate to 0.007 m. Measurements of hydraulic head were made in the remaining 31 wells using an electrical acoustic sounder, accurate to 0.005 m, to gain radial information about the cone of depression.

These measurements were made twice daily, either immediately prior to or after neutron moisture content logging.

The moisture content profile was logged along the access tubes using a Campbell Pacific Nuclear Corporation 503DR neutron moisture probe. This tool emits high-energy neutrons from a 50 mCi Americium-241/Berylium source and counts the number of thermal neutrons moderated enroute to a detector over a user specified time interval. The source center-detector center spacing for this device is 7.6 cm.

This experiment used a 4-s count time; the results were expressed in terms of the equivalent count rate for a 16-s window (the standard output for this instrument). A field calibration assuming a linear tool response between residual and full moisture content was used to convert the neutron count rate into the corresponding volumetric water content. Based on the statistics of the neutron count rate, the maximum uncertainty in volumetric water content was estimated to be 0.011.

The effective sampling volume of the neutron moisture probe is difficult to quantify due to the inherent complexities involved in modeling neutron transport. However, the size of this volume can be qualitatively evaluated by observing the tool response in characterized analogy systems. For this study, we examined neutron moisture results obtained by DeRyck (1994) that were collected in a large test cell (3 m diameter, 1.7 m depth) containing repacked Borden sand. The water content profile obtained from the neutron probe reproduced the laboratory water content-pressure head relationship acquired by Nwankwor (1982). These results indicate that this probe can define water content in the Borden aquifer on the scale of the source-detector spacing. In particular, it indicates that the transition zone in this system can be accurately monitored. These finding are consistent with our pre-test field results; the observed equilibrium transition zone thickness and its position above the static water table are comparable with the experimentally derived soil moisture characteristic curve.

Neutron logging was performed from a depth of 1.25–3.5 m below ground surface at a sampling interval of 0.05 m. This logging interval provided complete coverage of the transition zone throughout the entire experiment. This sampling interval permitted good definition of vertical variations in the moisture profile, allowing us to accurately monitor the shape and thickness of the transition zone.

4. Experimental results

4.1. Pumping test

4.1.1. Hydraulic head data and hydraulic gradients

The time-drawdown data for the deep-shallow observation well pairs located in the immediate vicinity of the neutron access tubes are shown in Fig. 3a–d. The magnitude and timing of drawdown varies systematically with both depth and radial distance; nearby deep wells show an earlier and greater response than shallower and more distant wells. The response observed on these log-log plots appears to be a typical three-stage curve for unconfined aquifers (Neuman, 1972). However, semi-log plots reveal a relative slowing in the drawdown rate after 5800 min (i.e. in the later part of the final stage) for all of the wells, indicating the possible interaction with a distant recharge boundary.

Fig. 4 shows the vertical hydraulic gradients below the water table obtained from the deep-shallow well pairs during the pumping test; these gradients were obtained using Eq. (2) given below. Prior to the test, vertical gradients were zero for all of the well pairs. For the pairs out to 5 m distance, a downward gradient develops immediately and reaches a maximum value within the first 10 min of pumping. The gradients slowly decrease throughout the remainder of the pumping test with significant gradients remaining at the end of pumping; on day 7, the vertical gradients were still 80 and 40% of their early-time maximums at 1 and 5 m, respectively. The magnitude of the gradient decreases with radial distance, being minimal at 15 m.

4.1.2. Moisture content data

Selected moisture content profiles (i.e. θ_w as a function of elevation) obtained before and during the pumping test for the four access tubes adjacent to deep-shallow observation well pairs are given in Fig. 5a–d. The pre-test transition zone thickness on the background profiles are between 0.40 and 0.45 m;

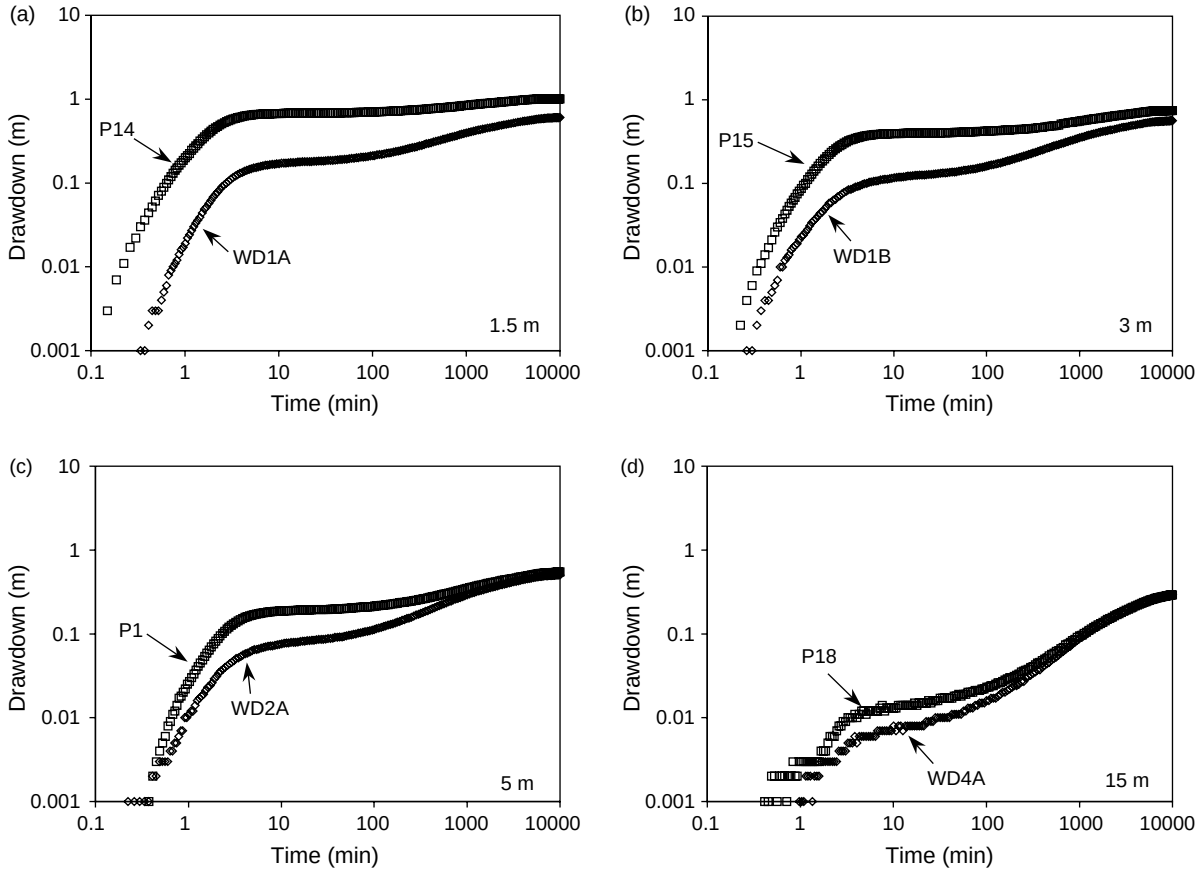

Fig. 3. Hydraulic head drawdown measured in deep-shallow observation well pairs. The radial distance from the pumping well is given in the bottom right corner of each graph.

considering the degree of aquifer variability, these values are consistent with the 0.40 m thickness reported by Nwankwor et al. (1992). Comparison of background hydraulic head values and the moisture content profiles gives values of pre-test capillary fringe thickness between 0.30 and 0.35 m, again consistent with the thickness of 0.30 m observed by Nwankwor et al. (1992).

It can be seen in Fig. 5 that drainage begins prior to 480 min, the time of the first cycle of moisture profile monitoring after the pumping commenced. The portion of moisture content profiles for $\theta_w > 0.15$ appear to translate downwards during pumping without significant changes in the character of that portion of the transition zone relative to the background profile. In particular, it can be observed that the transition zone slope in this region remains relatively constant

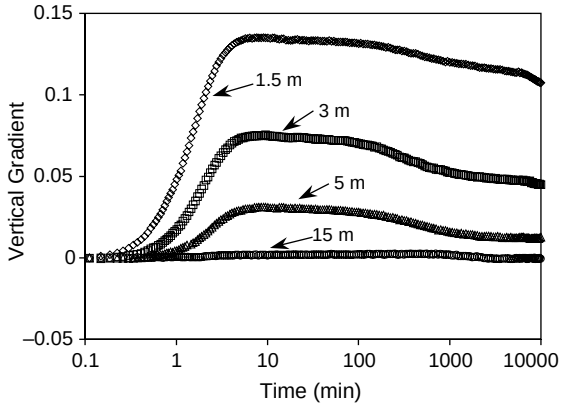

Fig. 4. Vertical hydraulic gradients during pumping measured in deep-shallow well pairs. Data for each well pair are identified in the figure by their radial distance from the pumping well. Positive values indicate downward gradients.

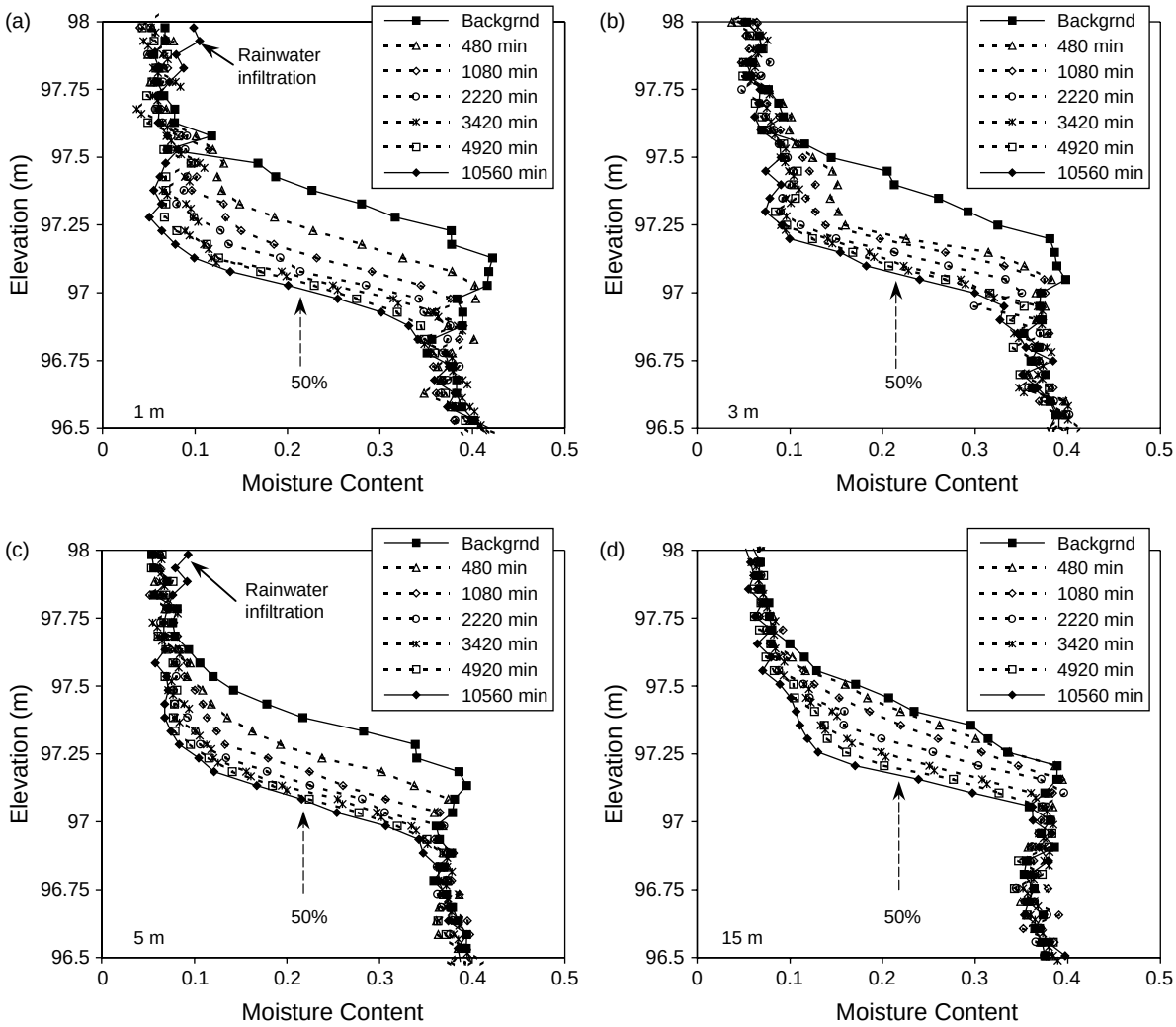

Fig. 5. (a–d) Moisture content profiles obtained before and at selected times during pumping test. Moisture profile reference point (i.e. $\theta_w = 0.22$, the 50% saturation level) is indicated. Radial distance from the pumping well is given in the bottom left corner of each graph. Elevation reference datum is the top of the pumping well casing (100.00 m); the ground surface is approximately 99.50 m.

throughout drainage. Minor deviations from this translation motion can be observed at the top of the transition zone (i.e. $0.07 \leq \theta_w \leq 0.15$) where moisture content is shifted to slightly higher θ_w values than would be expected from a purely downward shifting profile. These features persist up to 2200 min, gradually receding back to the residual θ_w level. Similar behavior is observed at these elevations during the recovery test, suggesting that a likely cause is vertical heterogeneity in the aquifer lithology which results in depth variations in the capillary pressure-water content relationship.

The late time profiles (i.e. 10,560 min) in Fig. 5a and c (at 1 and 5 m, respectively) show a possible infiltration event caused by rainfall which appears as a low amplitude pulse of elevated θ_w occurring at the top of the profiles. The appearance of this event at specific locations is mostly likely related to presence or absence of preferential vertical flow paths at a given site. At no time during the pumping test was this

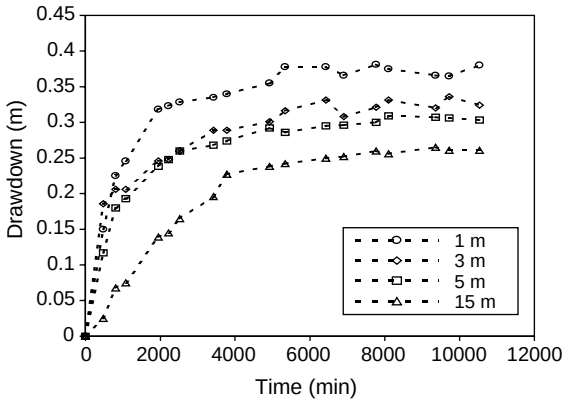

Fig. 6. Drawdown of moisture profile reference point (i.e. $\theta_w = 0.22$, the 50% saturation level). The legend gives distances from the pumping well.

feature seen to merge with the top of the transition zone, indicating that our observations of the transition zone were not significantly impacted by rainwater infiltration.

We propose that the predominate behavior of the moisture content profile during pumping can be represented in term of a downward translating profile. To quantify this behavior during pumping, the drawdowns of $\theta_w = 0.22$ point on the moisture content profiles (i.e. the midpoint value of θ_w between full and residual saturation) are displayed in Fig. 6. The choice of the midpoint value was an arbitrary one; however, the simple translation of the moisture profile during the test implies that movement of a reference saturation point in the profile will quantify that translation. The magnitude of moisture profile drawdown in Fig. 6 decreases with increasing distance from the pumping well. Also, the drawdown rate during the first 4000 min of pumping decreases with distance. At late times (i.e. greater than 6000 min), the drawdown rate has significantly slowed; and the moisture profile drawdown appears to have reached a constant rate.

4.2. Recovery test

4.2.1. Hydraulic head data and hydraulic gradients

Time-recovery data for the hydraulic head levels are shown in Fig. 7a–d. Analogous to the case during pumping, the deep observation wells closer to the pumping well show an earlier and greater response than shallower and more distant wells. A comparison of the temporal hydraulic head data for the pumping and recovery tests in Figs. 3 and 7 clearly shows systematic differences with radial distance and depth. The differences are particularly obvious during intermediate times (i.e. between 5 and 1000 min) when the pumping drawdown curves show a flattening stage. During this time period, the recovery curves continue to rise; this difference is greater for the shallower well in each pair at a given radial distance.

Vertical hydraulic gradients below the water table for the recovery portion of the experiment are displayed in Fig. 8; again, these gradients were determined using Eq. (2) given below. The vertical gradients responded to the cessation of pumping very quickly (i.e. within 1 min); the downward gradients rapidly reverse to upward gradients. A maximum upward gradient occurs within 10 min, after which they slowly diminish beyond the end of recovery monitoring. The magnitudes of the upward gradients are smaller than the corresponding downward gradients observed during pumping. The magnitude of the vertical gradient decreases with radial distance and is again essentially zero at 15 m.

4.2.2. Moisture content data

Moisture content profiles obtained during the recovery test are shown in Fig. 9a–d. In a manner analogous to drawdown, the portion of moisture content profiles for $\theta_w > 0.15$ translate upwards without significant changes in the slope of the transition zone relative to the pre-pumping background profiles. As mentioned above, the slightly higher θ_w values redevelop near the top of the transition zone (i.e. $0.07 \leq \theta_w \leq 0.15$) over the same elevation interval where they were observed during the pumping test. It is interesting to note that there is little recovery in the moisture content profiles during the time period up to first cycle of profiling done 240 min after the cessation of pumping. In addition, the moisture content profiles in Fig. 9a–c show the effect of entrapped residual air; the water content is slightly less than full saturation (i.e. $\theta_w = 0.35$ versus $\theta_w = 0.37$) below the transition zone as the moisture profile translates upwards. Comparison with the initial pre-pumping background profile clearly shows that recovery is incomplete after 5 days.

The infiltrating rainfall event noted in the moisture content profiles from the pumping portion of

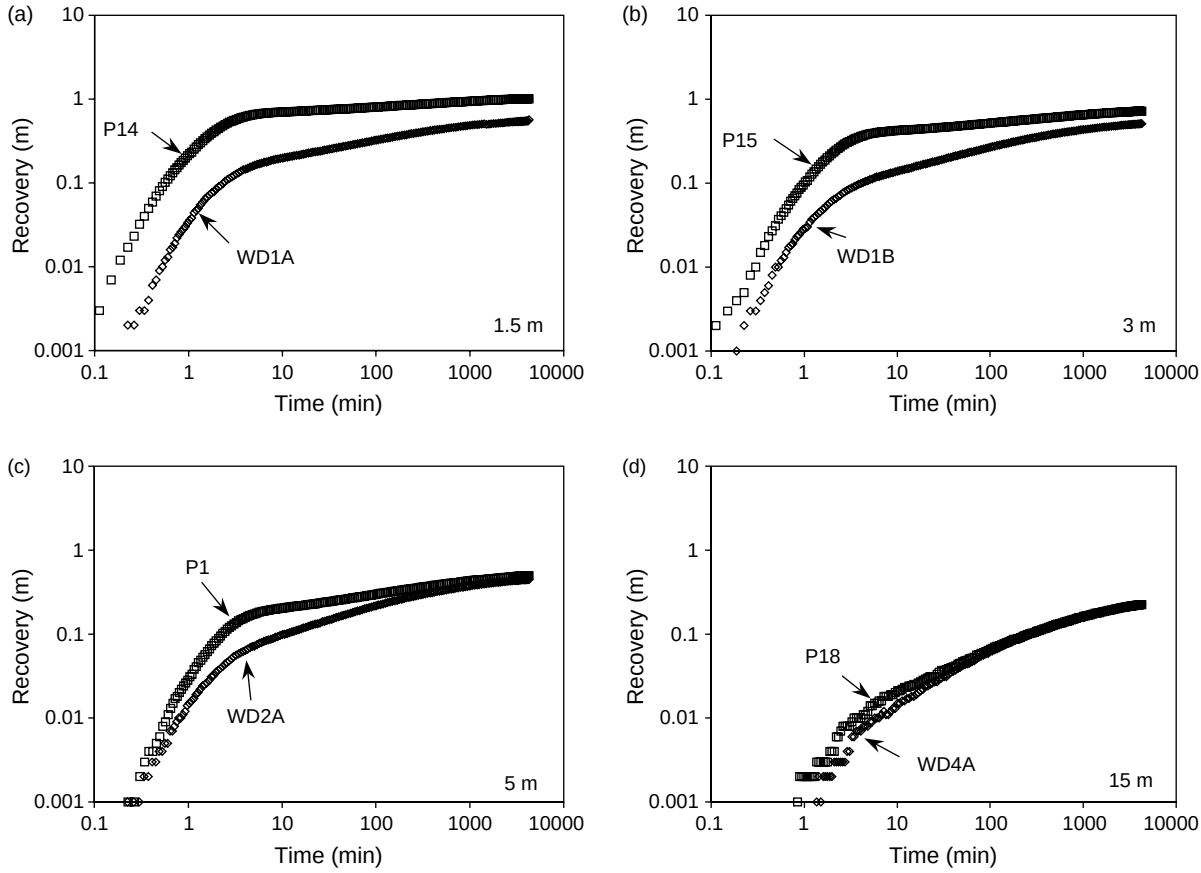

Fig. 7. Hydraulic head recovery measured in deep-shallow observation well pairs. The radial distance from the pumping well is given in the bottom right corner of each frame.

the experiment at radial distances of 1 and 5 m (Fig. 5a and c) is also observed during recovery (Fig. 9a and c). While this event appears to slightly elevate the residual water content, it does not significantly affect the general observations of the moisture profile response during recovery.

Similar to the pumping case, we propose that the predominate behavior of the moisture content profile during recovery can be represented as an upward translating profile. The recovery of the midpoint $\theta_w = 0.22$ value in the transition zone was again used to quantify this behavior; these results are displayed in Fig. 10. Again, the simple translation of the moisture profile during recovery implies that movement of a reference saturation point in the profile quantifies that translation. The magnitude of recovery relative to the maximum drawdown decreases with increasing radial

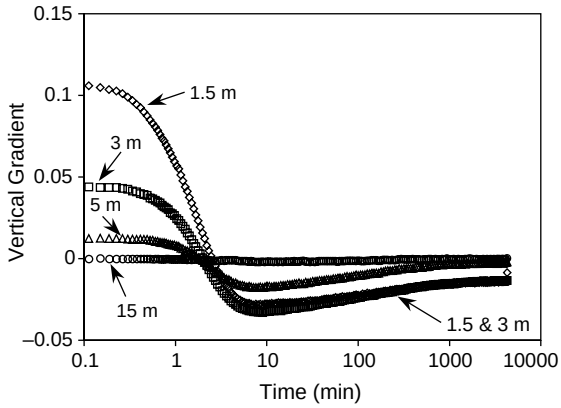

Fig. 8. Vertical hydraulic gradients during recovery (positive value is a downward gradient) measured in deep-shallow well pairs. Data for each well pair are identified in the figure by their radial distance from the pumping well. Positive values indicate downward gradients.

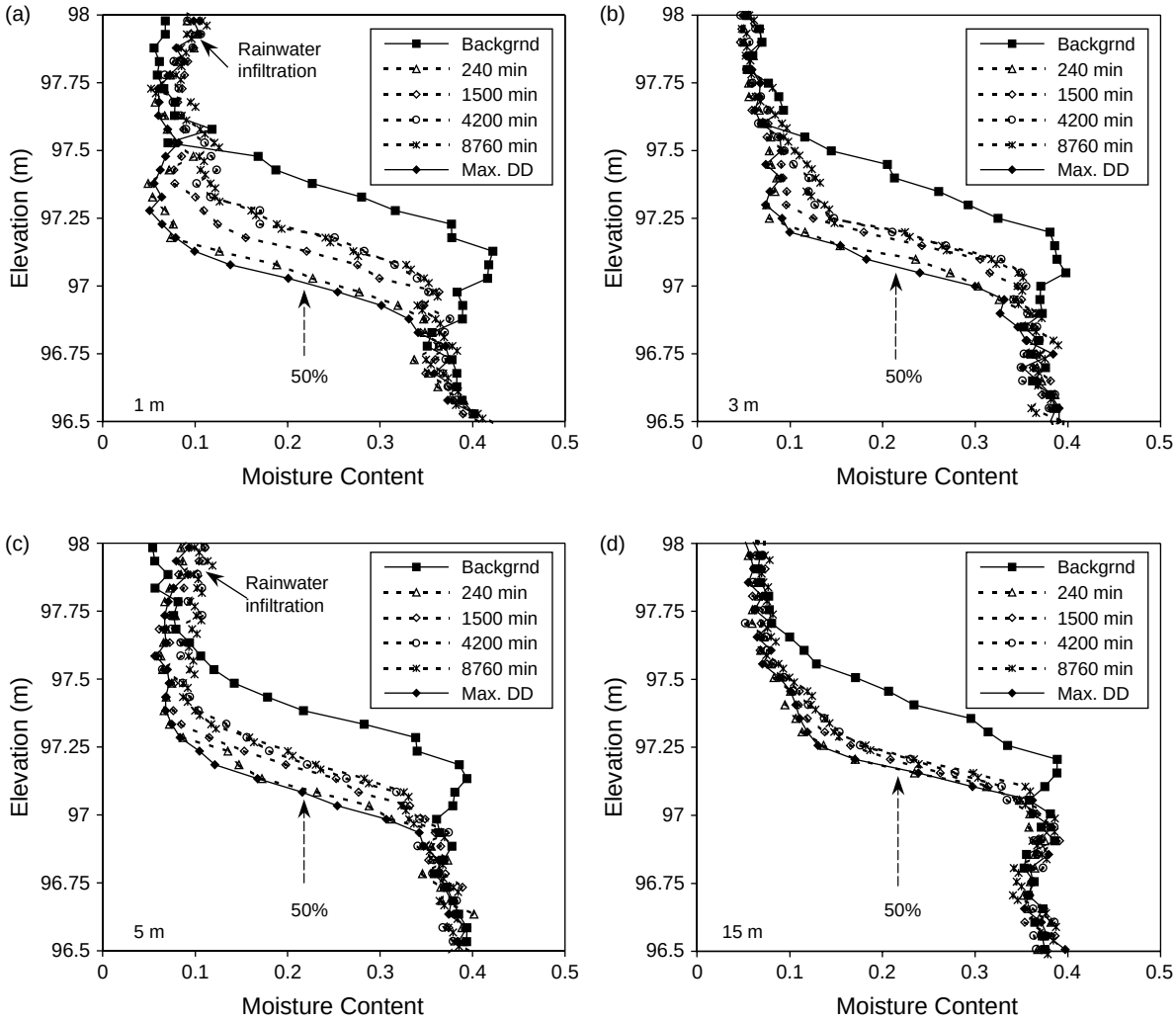

Fig. 9. (a–d) Moisture content profiles obtained at selected times during recovery; the profile for pre-pumping background conditions also shown. Moisture profile reference point (i.e. $\theta_w = 0.22$, the 50% saturation level) is indicated. Radial distance from the pumping well is given in the bottom left corner of each graph. Elevation reference datum is the top of the pumping well casing (100.00 m); the ground surface is approximately 99.50 m.

distance. Also, the rate of recovery lessens significantly up to about 4000 min; and little additional recovery occurs until the end of monitoring at 8760 min.

4.3. Relationship between the moisture content and hydraulic head

The combined temporal hydraulic head and moisture content data for three radial distances having deep-shallow observation well pairs (i.e. 3, 5 and 15 m) are shown in Fig. 11a–c. To illustrate the relationships between these two different data sets, they are displayed in terms of both elevation and drawdown relative to their pre-test positions. As was done previously, the $\theta_w = 0.22$ position on the moisture content profiles is used to quantify the their response as vertically translations.

The observation well pair at each radial distance was used to estimate the drawdown and elevation of

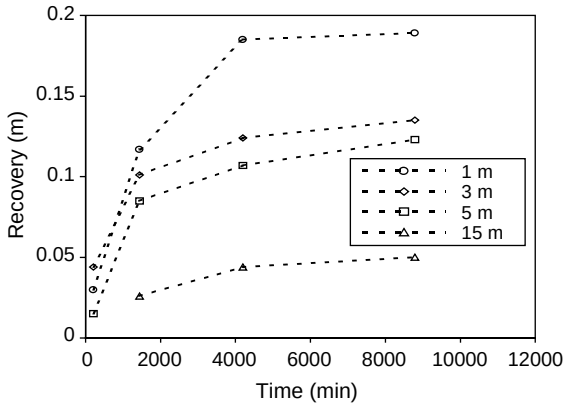

Fig. 10. Recovery of moisture profile reference point (i.e. $\theta_w = 0.22$, the 50% saturation level). The legend gives distances from the pumping well.

the water table (i.e. the surface at which pore pressure is equal to atmospheric pressure). It was assumed that at a given radial distance the vertical hydraulic gradient is not depth dependent; this assumption implies a linear head variation in the vertical direction. Since the vertical gradients below the water table were zero prior to pumping, the water table drawdown Δh^{wt} can be estimated from the hydraulic head data using (Endres et al., 2000)

$$\Delta h^{wt} = (\Delta h^u - m d^u)/(1 - m) \quad (1)$$

where Δh^u is the drawdown in the upper observation well and d^u is the depth below the pre-test water table to the screen of the upper well. The vertical hydraulic gradient m is given by

$$m = (\Delta h^b - \Delta h^u)/\Delta l \quad (2)$$

where Δh^b is the drawdown in the lower observation well and Δl is the vertical separation between the screened intervals of the well pair. The elevations of the water table during the test were estimated using the Δh^{wt} values. It can be seen in Fig. 11 that water table elevation and drawdown is almost identical to those of hydraulic head level in the shallow well.

Let us first consider the pumping portion of the experiment (i.e. 0–10,710 min.) for each radial distance in Fig. 11. It can be seen that the drawdown rates for the moisture profile, the water table and deeper hydraulic head values are greatest at early times and progressively decrease with increased duration of pumping. However, the hydraulic head and water table drawdowns are greater than moisture profile drawdown throughout the pumping test. For the two closer well pairs in Fig. 11a and b (radial distances 3 and 5 m, respectively), this differential drawdown increases significantly during the first 1000 min and slowly grows throughout the remainder of the pumping test. The differential drawdown at the far well pair (radial distance 15 m) develops at a much slower rate, and is only clearly discernable in Fig. 11c after 5000 min.

Assuming that the predominate behavior of the moisture content profile is a downward translating profile, the differential drawdown between the moisture profile reference point and the water table must result in an extension of the capillary fringe. This extension produces what Nwankwor et al. (1992) defined as excess capillary fringe storage. Given the inherent difficulty in precisely determining the top of the capillary fringe on the moisture profile, this extension has been quantified in Fig. 12 as the difference between the drawdown of the projected water table and the moisture profile reference point (i.e. $\theta_w = 0.22$) in the transition zone. For a vertically translating moisture profile, the movement of this reference point is equivalent to that of the top of the capillary fringe. It can be seen in Fig. 12 that a significant capillary fringe extension has developed by 480 min out to at least 5 m from the pumping well. The rate of extension slows with time and appears to become constant after 6000 min. It should be noted that there is a lateral displacement between the observation well for hydraulic head data (1.5 m radial distance) and the access tube for moisture content data (1 m radial distance). This displacement is significant at this short radial distance and is likely the cause of the thinner capillary fringe extension estimated for 1 m than at 3 m on this figure. At 15 m radial distance, detectable capillary fringe extension is not clearly observed until 6000 min.

Now let us consider the recovery portion of the experiment (i.e. 10,710–19,500 min.) in Fig. 11a–c. Analogous to the drawdown rates, it can be seen that the recovery rates for the moisture content profile, hydraulic head and the water table are greatest at early times and progressively slow with additional recovery time. However, the magnitude of the hydraulic head and the water table recoveries are much larger than

the moisture profile recovery. This differential recovery has implications for the capillary fringe thickness, shrinking it from the maximum extension attained at the end of the pumping test. This shrinkage can be seen in estimated capillary fringe extension given in Fig. 12. The collapse of pumping-induced extension occurs rapidly after the start of recovery (i.e. within 240 min), and a compression of the capillary fringe relative to its pre-pumping thickness quickly develops. The compression rate significantly slows with time. Interestingly, the magnitudes of the capillary fringe compression converge to 0.15 m at late time for all four radial distances; this differs significantly from the radial variation of the capillary fringe extension during the late stage pumping. This compression effectively converts the capillary fringe from a state of excess storage to one of storage deficit, and significant storage deficit is present after 5 days of recovery.

By 15,000 min in Fig. 11a, the deep well at 3 m radial distance has essentially recovered all of the hydraulic drawdown that occurred during pumping;

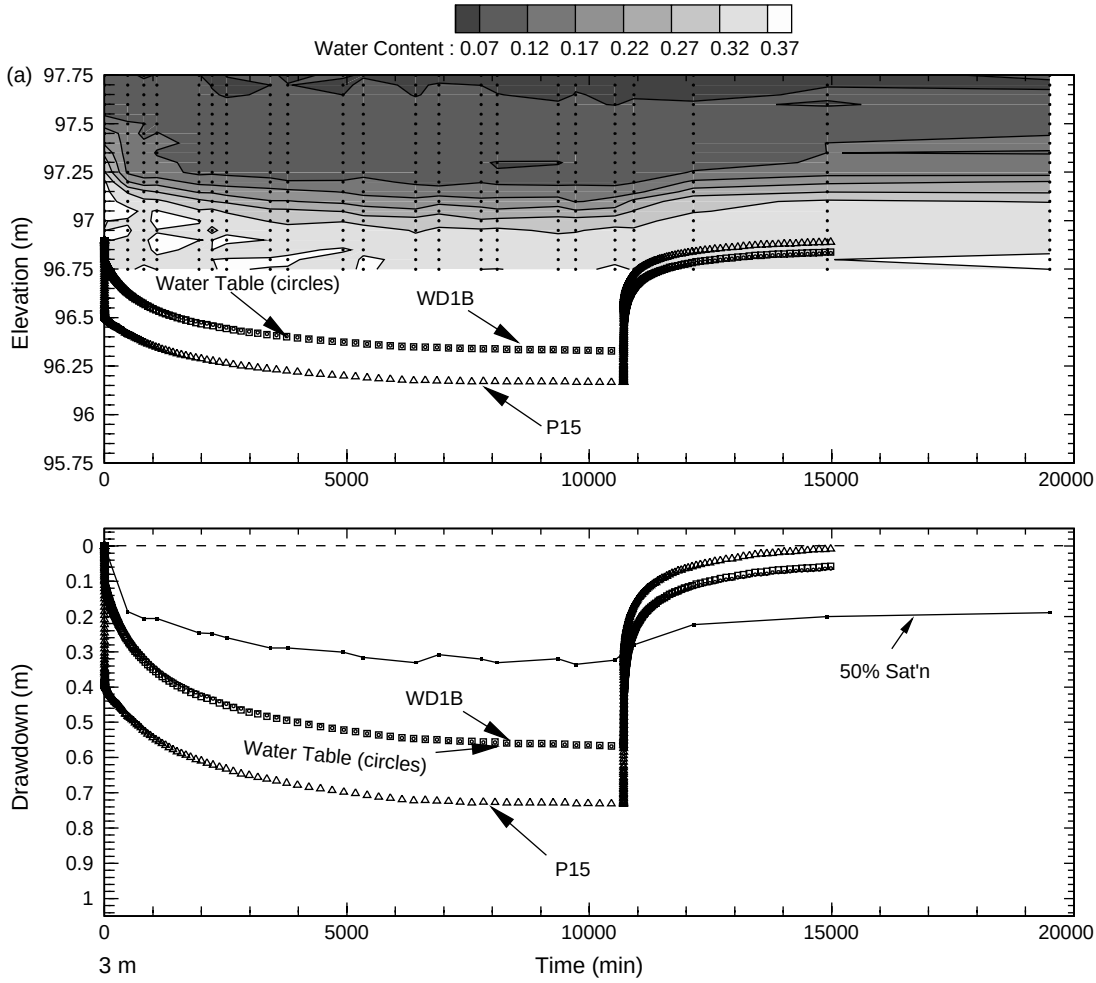

Fig. 11. (a–c) Moisture content distribution and hydraulic head measurements for deep-shallow well pair during pumping and recovery. Water table inferred well pair also shown. Pump was turned off at 10,710 minutes. Radial distance from pumping well indicated in lower left. Elevation reference datum is the top of the pumping well casing (100.00 m); the ground surface is approximately 99.50 m. Top panel: Contoured moisture content data, hydraulic head measurements and inferred water table as a function of elevation. Lower panel: Time-drawdown graph for moisture profile reference point (i.e. $\theta_w = 0.22$, the 50% saturation level), hydraulic head and inferred water table.

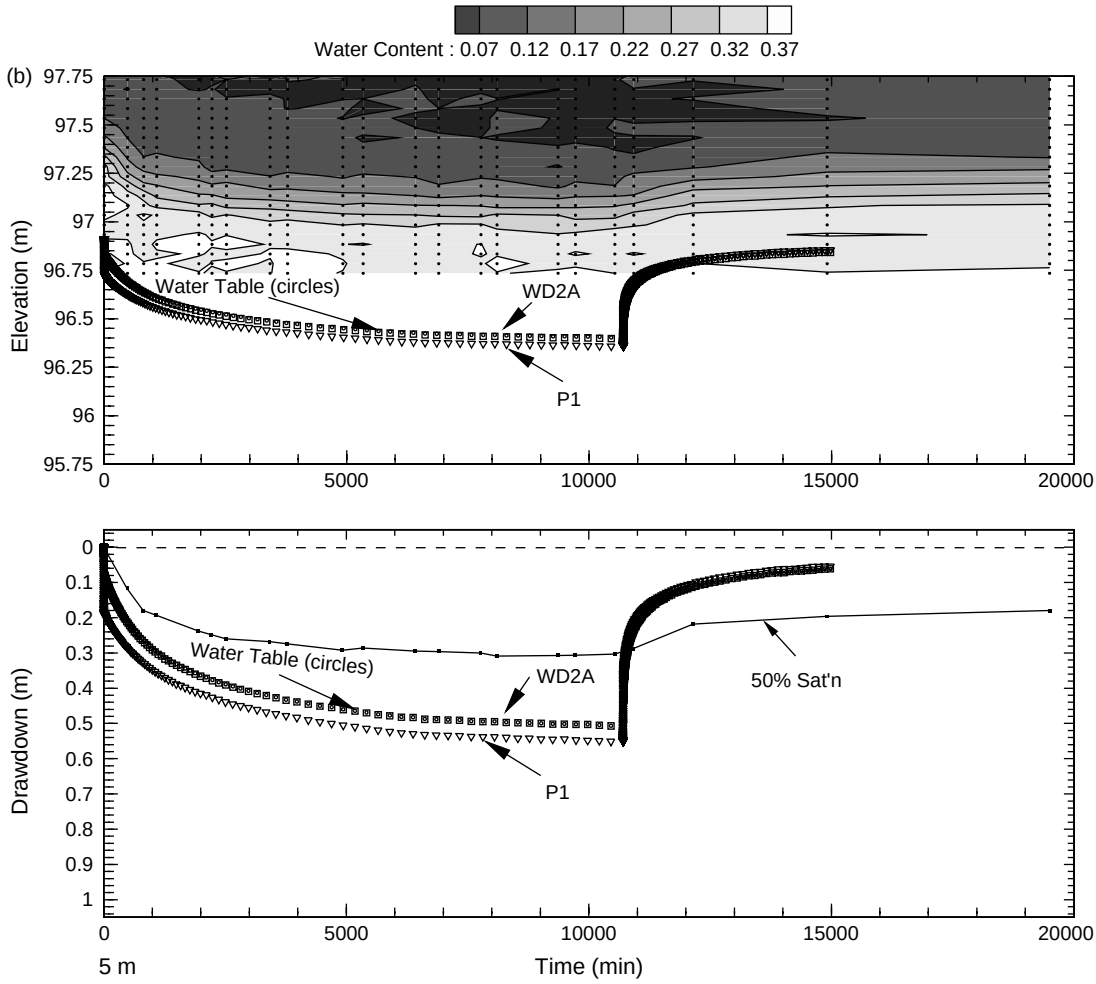

Fig. 11 (*continued*)

the shallow well at this radial distance remains about 0.05 m below its pre-pumping levels. At radial distances of 5 and 15 m in Fig. 11b and c, respectively, all hydraulic head levels have recovered to about 0.05 m of their pre-pumping levels. However, the moisture profile recovery in Fig. 11a–c is substantially less than that of the hydraulic heads. The moisture profile has only recovered to a level about 0.20 m below its pre-pumping elevation at all three radial distances. This recovery deficit correlates with the 0.20 m pressure difference between experimental drainage and imbibition curves for Borden aquifer material obtained by Nwankwor (1982).

The radial relationships between the hydraulic head measurements and the moisture profile reference point for the distance-drawdown and distance-recovery data are shown in Figs. 13 and 14, respectively. Hydraulic head data from 36 spatially distributed observation wells are displayed on these figures; the differences in hydraulic head drawdown at similar radial distances are likely a result of textural heterogeneities across the site and variations in screen depths.

The hydraulic head drawdowns in Fig. 13a–d are greater than moisture profile drawdowns to a radial distance of 20 m for all times. This differential

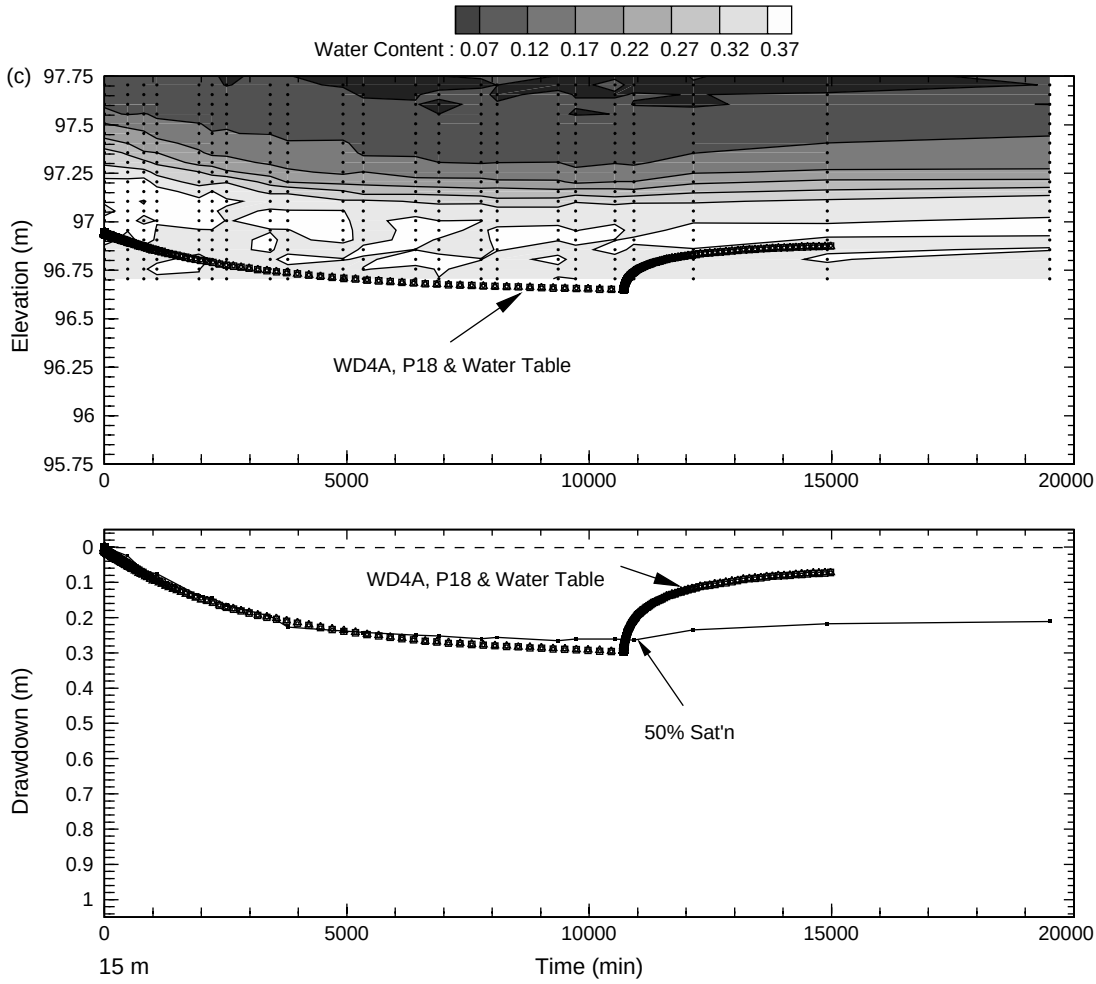

Fig. 11 (*continued*)

drawdown progressively decreases with radial distance. Extrapolating the experimental observations, it was conjectured that at some distance the drawdowns of the moisture profile and hydraulic head levels are equal throughout this pumping test. To estimate this distance of equal drawdown, 2nd order polynomial functions were fit to the moisture profile and shallow observation well data. For the sampling times shown on Fig. 13, these functions consistently intersect between 20 and 25 m, implying that differential drawdown is zero at distances beyond this range.

The spatial relationship between the hydraulic heads and moisture profile during recovery in Fig. 14a–c is different than that during drawdown. After 200 min of recovery, the hydraulic head levels have risen to nearly the same residual drawdown level across the entire site. After this time, the hydraulic head levels appear to rise uniformly at all radial distances. Most of the observed moisture profile recovery out to a radial distance of 15 m occurred within 1500 min; the moisture profile rose to about 0.20 m below its pre-pumping level and appears to have stabilized. However, the moisture profile at 20 m radial distance does not begin to recover until 1500 min and rose well above the 0.20 m drawdown level observed at shorter radial distances by 4300 min. It should be noted that the maximum moisture profile drawdown during pumping at 20 m did not exceed

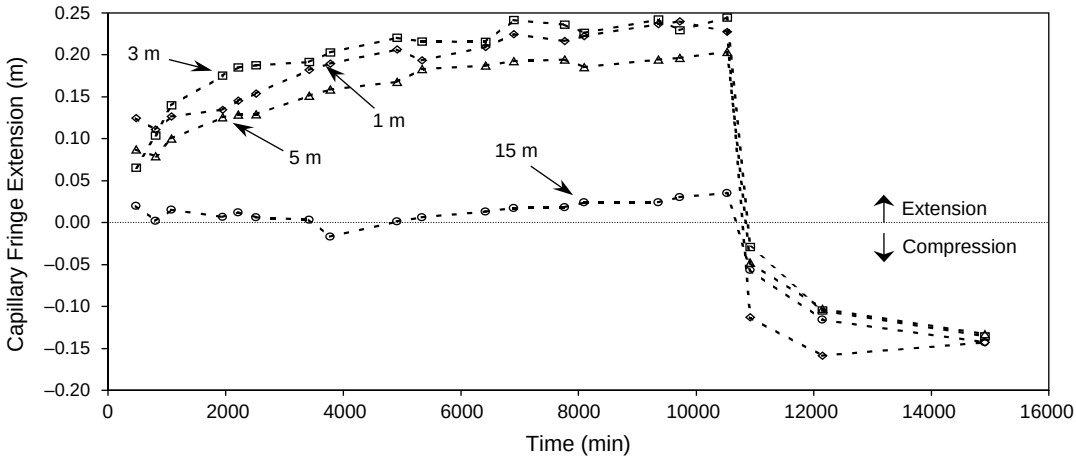

Fig. 12. Capillary fringe extension estimated from moisture profile and water table drawdowns for pumping and recovery. Positive value indications increased thickness relative to static value; negative value denotes decreased thickness relative to static value. Pump was turned off at 10,710 min. Distance from the pumping well is indicated for each data set.

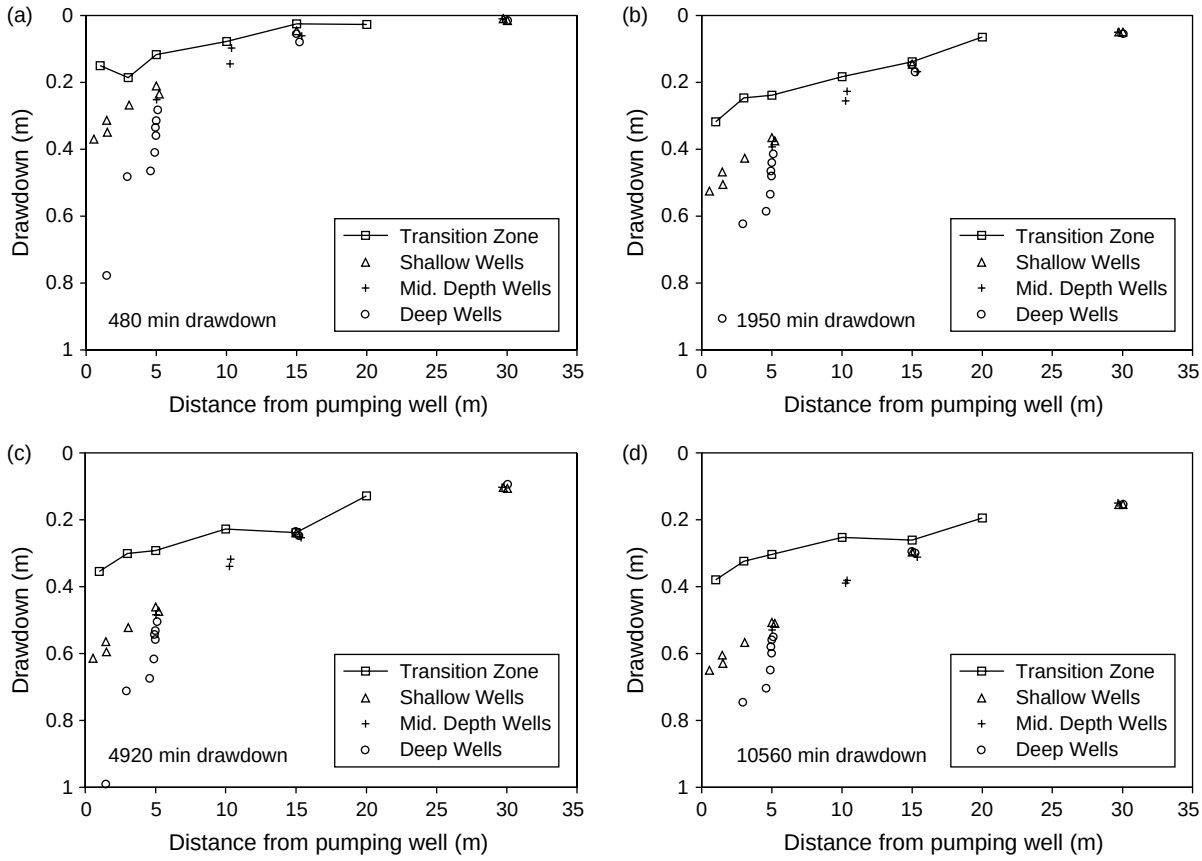

Fig. 13. (a–d) Distance-drawdown of hydraulic heads and moisture profile reference point (i.e. $\theta_w = 0.22$, the 50% saturation level) for selected times during pumping. Pumping time is given in the bottom left corner of each graph.

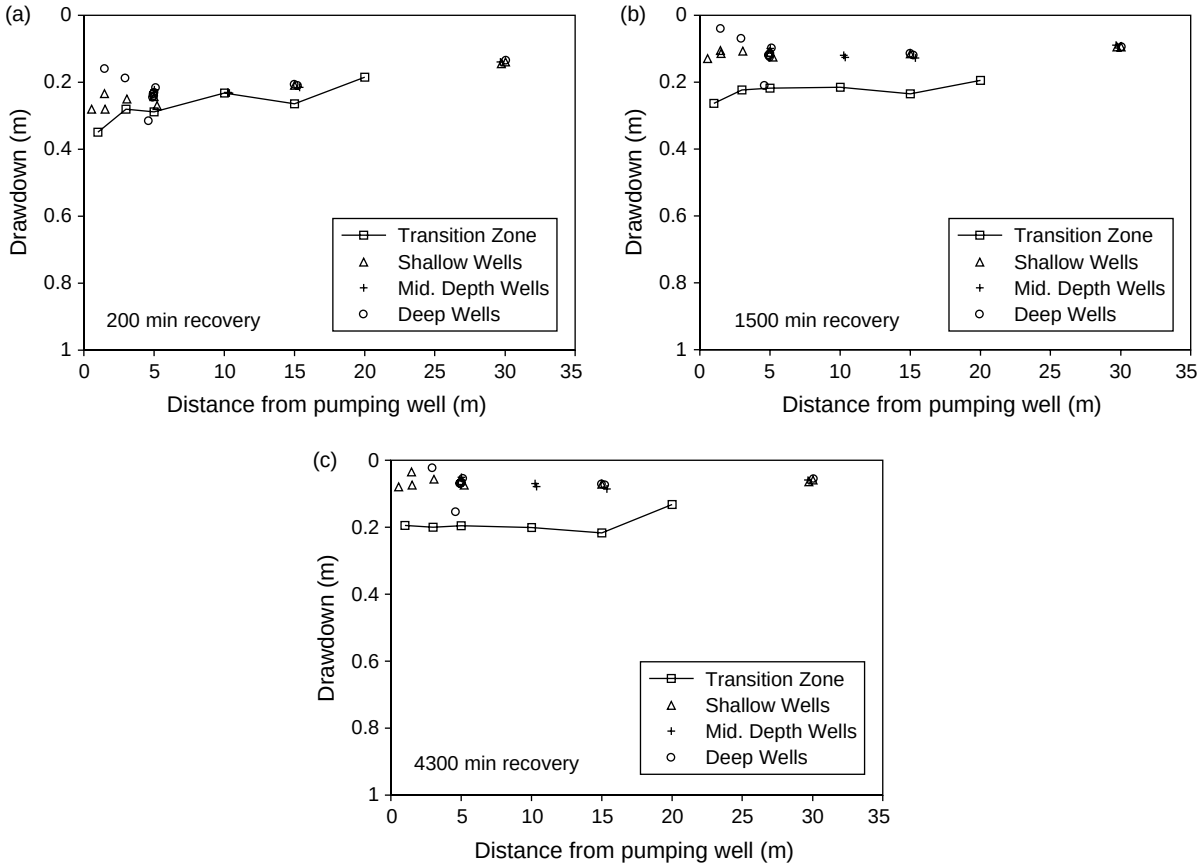

Fig. 14. (a–c) Distance-drawdown of hydraulic heads and moisture profile reference point (i.e. $\theta_w = 0.22$, the 50% saturation level) for selected times during recovery. Recovery time is given in the bottom left corner of each graph.

0.20 m whereas profile drawdowns greater than 0.20 m occurred out to a radial distance of 15 m.

5. Discussion

It is important to place the results of this experiment in the context of previous work on the behavior of unconfined aquifers during pumping and recovery. In particular, can we evaluate the commonly held assumptions and hypotheses about unconfined aquifer response? Further, how do our experimental results relate to the work of Nwankwor and others at this test site?

The hydraulic head drawdowns at a specific radial distance are greater than the corresponding moisture profile drawdown throughout this pumping test; this differential lessens with increasing radial distance. The water table drawdown inferred from the deep-shallow observation well pairs is also greater than the moisture profile drawdown. This finding indicates that the assumption of instantaneous drainage from above the declining water table used by the Neuman models (e.g. Neuman, 1972; 1974) does not describe the behavior of this unconfined aquifer at shorter radial distances.

This differential drawdown between the transition zone and inferred water table produces an extension of the capillary fringe as identified previously by Nwankwor et al. (1992). This extension results in the formation of excess capillary fringe storage that progressively increases and does not diminish at late-times. This persistent excess storage differs from the behavior reported by Nwankwor et al. (1992) who

stated that the formation of excess storage appeared to decrease significantly in the intermediate stages of pumping and essentially disappeared by approximately 1500 min in their experiment.

The volume-balance method for estimating specific yield assumes that the drained aquifer volume corresponds to the water table drawdown cone. Nwankwor et al. (1984) recognized that differential drawdown between the moisture profile and water table would produce underestimates of specific yield. Using the hydraulic head drawdowns from shallow wells to estimate water table response, their specific yield estimates from the volume-balance method increase with pumping duration and converge to the laboratory measured value of 0.30 after 65 h. They inferred from this behavior that the effects of differential drawdown progressively diminished with time and distance from pumping well; therefore, late-time shallow well data can be used to determine specific yield by the volume-balance approach. However, our observed persistence of the excess capillary fringe storage in the vicinity of the pumping well and its progressive late-time development at greater distances means that even long-term hydraulic head drawdowns from shallow wells do not accurately describe the drained volume in this unconfined aquifer. Hence, while the Nwankwor et al. (1984) method appears to give reasonable specific yield values, its assumptions do not coincide with our observations.

The predominate behavior of the moisture content profile is a downward translation during this pumping test. Further, drainage to residual saturation above the transition zone occurs with the downward translation of moisture profile. These two observations indicate that there is minimal excess storage above the capillary fringe at late times. This observation is counter to the suggestion by Grimestad (2002) that significant quantities of excess moisture become more or less permanently trapped within the region above the capillary fringe.

It is commonly assumed that vertical hydraulic gradients have a significant effect on flow in unconfined aquifers during pumping. In this experiment, these gradients would result from the combined effects of the partially penetrating pumping well and the progressively deepening depression of the upper bounding surface in the vicinity of the pumping well. We observed vertical gradients below the water table that quickly formed after the start of pumping and rapidly reached their maximums within 10 min. While the magnitudes of the vertical gradients decreased, they remained a significant fraction of their early-time maximum values until the end of the pumping test. This condition indicates that significant vertical flow exists below the water table in the vicinity of the pumping well throughout the test. Our observations support the assertion by Neuman (1979) that vertical gradients are a significant component in the flow to the pumping well in an unconfined aquifer system. However, our gradient behavior differs from those described in Nwankwor et al. (1992); they stated that the vertical gradient in the saturated zone at 5 m radial distance decreased by almost 90% after 1000 min of pumping and trended towards zero at 1500 min.

A direct relationship between the vertical gradients below the water table and the excess capillary fringe storage during pumping is not apparent from these experimental data. While the magnitudes of both quantities decrease with radial distance, their temporal behaviors at a given distance vary significantly; vertical gradients quickly reach a maximum and gradually decrease while the excess capillary fringe storage progressively increases. In addition, excess capillary fringe storage occurs in the present experiment at a radial distance of 15 m where vertical gradients are very small. In comparison, Nwankwor et al. (1992) reported that the temporal response of vertical gradients in the saturated zone and the formation of excess capillary fringe storage are similar.

The degree of total recovery relative to pre-pumping conditions is significantly less for the moisture profile than for the hydraulic heads. While the hydraulic head levels recovered to about 0.05 m below their pre-pumping levels, the moisture profile recovery stabilizes at a quasi-steady state level that is 0.20 m below its pre-pumping elevation for radial distances out to 15 m. This evidence, along with the entrapped residual air is seen below the upward translating transition zone, are strong indications that significant hysteretic processes are occurring above the water table at the field scale. The presence of these processes has potentially serious

implication for the recovery data analysis. The Neuman model that is used for recovery data analysis assumes drainage is completely reversible (Batu, 1998; Kruseman and de Ridder, 2000); hysteretic processes are not incorporated into this formulation.

6. Conclusions

The present experiment provides interesting field scale observations about the drainage occurring above the water table during pumping, as well as their relationships to the hydraulic head measurements from below the water table. Allowing for the effects of lithologic variations, the response of the water content profile is predominately characterized by a downward translation during pumping-induced drainage. Further, water content above the transition zone drained to residual saturation. These two observations imply that there is minimal excess storage above the capillary fringe at late times.

The drainage due to the translational behavior of the water content profile can be quantified by observing the drawdown of a set reference point (i.e. $\theta_w = 0.22$ midpoint) within the transition zone. The moisture profile drawdown at a given radial distance from the pumping well is consistently less than the corresponding hydraulic head drawdowns measured below the water table throughout the seven day test. The moisture profile drawdown is also less than the water table drawdown estimated from the deep-shallow observation well pairs during the entire pumping test.

The differential drawdown between the moisture profile and the water table results in capillary fringe extension and the formation of excess capillary fringe storage. This storage progressively grows during pumping and does not lessen at late-times. The rate of capillary fringe extension slows with time and eventually appears to become constant. The region of excess capillary fringe storage is not limited to the immediate vicinity of the pumping well (i.e. a radial distance up to 5 m from the pumping well). While its magnitude is small, differential drawdown and the resultant excess storage are evident to a radial distance of 15 m after 5000 min of pumping. Extrapolating the drawdown-distance data for the transition zone and shallow observations wells, it was estimated that capillary fringe extension and excess storage eventually extended out to between 20 to 25 m from the pumping well. This inference is significant for even a small amount of extension at these large radial distances implies a large contribution to the total volume of excess storage.

Vertical hydraulic gradients below the water table due to the partially penetrating pumping well and the depressed upper bounding surface formed soon after the initiation of pumping, reaching their maximums within 10 min. While these gradients diminished throughout the remainder of the test, they were a significant fraction of their maximum values at late times. A direct relationship between the vertical gradients below the water table and the excess capillary fringe storage during pumping is not apparent from these experimental data.

The recovery portion of this experiment also provided a number of important field scale observations about the imbibition occurring above the water table during recovery and its correlation with the hydraulic head measurements from below the water table. A comparison of temporal hydraulic head data for the pumping and recovery test clearly shows systematic differences with radial distance and depth, particularly during intermediate stage. The drawdown curves exhibit a relative fiat response while the recovery curves continue to rise. These differences are not unexpected given the differences in boundary conditions for these two types of tests. In particular, pumping-induced drawdown is driven by the extraction of water from the pumping well; during recovery, the hydraulic head changes are driven by horizontal hydraulic gradients between the drawdown cone and regions of the aquifer beyond the zone of influence.

Analogous to the pumping test observations, the response of the moisture content profile during recovery is essentially an upward translation. However, the magnitude of the hydraulic head recovery is greater than the moisture profile recovery. This recovery differential leads to a compression of the capillary fringe to a thickness less than its static value. The amount of compression converges to a uniform 0.15 m value at late recovery time for radial distances out to 15 m. This response is distinct different from the radial variation of the capillary fringe extension during the late stage pumping. The compression

effectively converts the capillary fringe from a state of excess storage to one of storage deficit. Hence, significant storage deficit is present after 5 days of recovery.

While hydraulic heads measurements returned to within 0.05 m of their pre-pumping level after 5 days, the transition zone recovery remained 0.20 m below its pre-pumping elevation for radial distances out to 15 m. This recovery deficit and the entrapped residual air observed below the upward translating transition zone are strong indications that significant hysteretic processes are occurring above the water table at the field scale.

Vertical hydraulic gradients below the water table also appear to be a significant component of the flow during recovery. These gradients reverse direction very soon after the initiation of recovery. While their maximum values are attained within 10 min of recovery, significant gradients persist throughout the duration of recovery monitoring out to a radial distance of 3 m. However, a direct relationship between the vertical gradients below the water table and moisture profile recovery is not clearly discernable from our experimental results.

The results of this field-scale study clearly illustrate the complexity of the moisture content profile response and its relationship to hydraulic head measurements below the water table during both pumping and subsequent recovery. What now needs to be resolved is whether these observations can be simulated with existing models for unconfined aquifer response. This question will be the focus of our future investigations.

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