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Seasonal variation of moisture content in unsaturated sandstone inferred from borehole radar and resistivity profiles

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Abstract

Understanding the processes controlling recharge to aquifers is critical if accurate predictions are to be made on the fate of contaminants in the subsurface environment. In order to understand fully the hydrochemical mechanisms in the vadose zone it is essential that the dynamics of the hydrology can be suitably characterised. The correlation between moisture content and both bulk dielectric and resistivity properties of porous media is well established. Using suitably placed sensors in boreholes detailed depth profiles of dielectric and resistivity behaviour have been monitored over a period of two years at a Triassic Sherwood Sandstone aquifer field site at Hatfield, England. The borehole–borehole transmission radar and borehole resistivity profiles show a significant correlation. Through appropriate petrophysical relationships, derived from core samples, seasonal dynamics of the vadose zone are seen to illustrate the migration of wetting and drying fronts over the monitoring period. At a second field site in Eggborough, located 17 km from Hatfield, similar temporal changes in moisture content in the sandstone were observed using borehole radar profiles. Travel times of seasonal wetting fronts through the sandstone at both sites appear to be approximately 2 m per month. The retardation of this front propagation in the top 3 m is also common to both sites, suggesting that pollutant transport may be principally controlled by near surface sediments. The results have important consequences to existing groundwater modelling programmes that are being utilised to predict transfer of agricultural chemicals through the vadose zone.

Keywords: Resistivity; Ground penetrating radar; Unsaturated flow

1. Introduction

In the UK, the Permo-Triassic Sherwood Sandstone is a major groundwater resource and is subject to increasing demand for public and private water supply. After the Chalk, the Permo-Triassic Sandstone aquifer group is second most important aquifer for groundwater resources in the UK. Allen et al. (1997) estimate that licensed abstraction in the sandstone accounts for approximately 25% of all UK groundwater abstraction. The aquifer is threatened by heavy chemical loading from agricultural and industrial practices and consequently models are required in order to assess travel times and attenuation within the unsaturated zone. Despite such importance, however, attempts to characterise the unsaturated flow and transport properties of the Sherwood Sandstone are rare. Most research to date has focussed on the study of transport of leachate from specific landfills (see Lewin et al., 1994; Thornton et al., 2000). Few attempts have been made to characterise unsaturated hydraulic processes in the sandstone, which are essential for reliable assessments of the vulnerability of the aquifer.

Unsaturated hydraulic characterisation may be

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achieved with conventional hydrological measurement techniques, such as neutron probes, TDR, and tensiometry. However, these techniques have restricted measurement scales, typically in the order of centimetres. Heterogeneity of the subsurface occurs at much larger scales and thus more appropriate measurement techniques are required. Furthermore, the measurement scale of these conventional soil moisture sensors are several orders smaller than the model grid scale for any practical hydrological predictive tool. Driven by the need for larger-scale measurements, there is growing interest in the use of geophysical methods for hydrogeological characterisation. Due to the sensitivity of resistivity and dielectric permitivity to volumetric moisture content, resistivity and ground penetrating radar (GPR) tools, in particular, have shown great value in aiding hydrological studies of the vadose zone.

Investigations of vadose zone processes have typically used surface deployed surveys, for example, using direct current (dc) resistivity (Kean et al., 1987; Frohlich and Parke, 1989; Benderitter and Schott, 1999), or GPR profiling (Greaves et al., 1996; van Overmeeran et al., 1997; Huisman et al., 2001). Both techniques are inappropriate for monitoring small changes at depths greater than a few metres, recognising that changes in moisture content at these depths are likely to be only a few percent. In the case of GPR, significant attenuation from highly electrically conductive near surface sediments restricts depth penetration of signals. In the case of dc resistivity, sensitivity at depth is limited with surface deployed electrodes due to restricted resolution. In addition, given the non-uniqueness of inversion methods for surface dc resistivity soundings (as demonstrated by, for example, Simms and Morgan (1992)), the uncertainty bounds in modelled resistivity values are likely to be greater than the resistivity variation caused by natural changes in moisture content.

Recognising the limitation of surface deployed surveys, a number of studies have utilised cross-borehole tomographic imaging of resistivity (for example, Slater et al., 2000; Daily et al., 1992) or radar (for example, Hubbard et al., 1997; Eppstein and Dougherty, 1998). Most previous applications, however, have concentrated on monitoring forced loading of the system by the use of tracer tests. Although these can offer valuable insight into likely solute pathways, they do not address what happens under natural recharge conditions. By creating artificially high contrasts in moisture contents due to tracer injection, the contrasts in the subsurface geoelectrical properties are also high, in comparison to those normally encountered. Furthermore, the typically short duration of tracer experiments does not permit an assessment of the extent of apparent changes due to noise in the system; say due to degradation of electrode contact in the case of resistivity surveys. In a recent study, Zhou et al. (2001) used a combined surface–borehole electrode array to map natural changes in resistivity due to rainfall inputs. In their investigation only short duration events (several days) and near surface (top 1.5 m) changes were studied.

In a recent study Binley et al. (2001a) demonstrated how cross-borehole GPR may be used to characterise vadose zone flow at a site in the UK Triassic Sherwood Sandstone. They used tomographic methods to determine changes in moisture content due to forced (tracer) and natural hydraulic loading at the site. Binley et al. (2001a) also show how radar profiling methods may be used to study one-dimensional changes in moisture content. We build on this preliminary study here by comparing moisture contents derived from borehole GPR surveys with those determined from borehole resistivity profiles. The study was carried out over a period of over two years, allowing comparison of changes with estimated net rainfall inputs. In addition, a comparison is made of borehole GPR results from a second field site to show the consistency in responses.

2. Field instrumentation

Two field sites were selected based on the following criteria: (i) close proximity to a sand/gravel quarry permitting detailed larger scale hydrogeological surveys, (ii) minimal drift cover, (iii) flat topography and reasonably undisturbed grass cover. One of the sites, located near Hatfield, South Yorkshire at the Lings Farm smallholding (National Grid Reference SE 653 079), was instrumented during June/July 1998. At the second site, located near Eggborough, North Yorkshire (National Grid Reference SE 570 232), a field study area was selected and instrumented in July 1999. The two sites are approximately 17 km apart (see Fig. 1) and are examples of potentially highly vulnerable 'sandstone islands'—a term used by UK environmental regulators to indicate areas of relatively clay-free drift deposits that allow direct and rapid recharge to the underlying sandstone aquifer relative to clay-covered areas. Since such areas permit potentially rapid, poorly attenuated, contaminant transport to the water table, the hydrological characterisation is essential for accurate vulnerability evaluation.

The sites were instrumented to permit a detailed hydrogeophysical study of vadose zone flow due to natural and forced (tracer) loading. The instrumentation was designed to allow both radar and resistivity tomographic imaging in addition to borehole profiling. Binley et al. (2002) present results from two-dimensional and three-dimensional cross-borehole resistivity imaging at the Hatfield site during a tracer test in October 1998, while Binley et al. (2001a) show cross-borehole radar tomography results during a further tracer test in February 1999. Binley et al. (2001a) also show changes in the radar tomograms due to natural loading during a 12 month monitoring period at the Hatfield site.

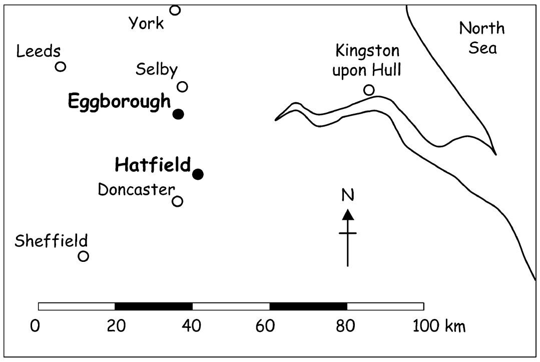

Fig. 1. Location of Hatfield and Eggborough sites in Northern England.

2.1. Instrumentation at the Hatfield site

Seven boreholes were drilled at the Hatfield site using 127 mm diameter tip rotary air-flush to a depth below the water table (approximately 12 m). Two of the boreholes (labelled H-R1 and H-R2, 5 m apart) were drilled for deployment of borehole radar. Fig. 2 shows the borehole layout at the Hatfield site. Due to the weakness of the sandstone a 76 mm diameter PVC casing was installed in H-R1 and H-R2, surrounded by a sand/cement backfill. The other boreholes were installed for dc resistivity measurements in both cross-hole and single-hole mode. In one of these boreholes (labelled H-B) located approximately 53 m from the midpoint of H-R1 and H-R2 (see Fig. 2), 32 stainless steel mesh electrodes were installed at 0.42 m spacing between depths of 0.42 and 13.44 m. In October; 1998 a 102 mm diameter core (labelled H-M) was extracted from the Hatfield site, approximately 20 m from H-R2, 30 m from H-B. In October 2000 an additional core was extracted (labelled H-AC), 5 m from H-M. From analysis of the cores, the sandstone sequence at the site consists of fluvially derived fining upwards sequences 1–3 m thick, grading from medium grained to fine-grained sandstone. Drift cover (mainly sand, gravels and cobbles) at the site is typically 2 m thick.

2.2. Instrumentation at the Eggborough site

Eleven boreholes were drilled at the Eggborough site during June 1999, as at Hatfield using 127 mm diameter tip rotary air-flush to a depth below the water table (approximately 17 m at the Eggborough site). Fig. 3 shows the borehole layout at the Eggborough site. In March 2000 a further borehole (labelled E-D, as shown in Fig. 3) was drilled and cored. Lithology was observed to be similar to that in the Hatfield core. Medium grained sandstone comprises the bulk of the core, although fine and medium sandstone sub-horizontally laminated on a millimetre scale was observed. Pokar et al. (2001) document hydraulic and physical properties of core samples from both the Eggborough and Hatfield sites.

As at the Hatfield site, a number of boreholes were drilled for geoelectrical tomographic surveys at Eggborough. Binley et al. (2001b) show that the cross-borehole radar and resistivity tomograms reveal similar layered structures. From analysis of conventional borehole logging results Binley et al. (2001b) also show that the layering at the Eggborough site extends over tens of metres. The focus here will be results obtained from two pairs of boreholes drilled for radar transmission surveys. One pair (E-A, E-B) was drilled with a separation of (4.91 m), the other

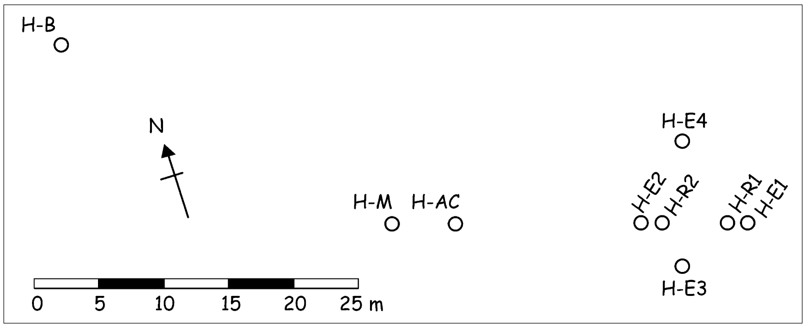

Fig. 2. Borehole layout at the Hatfield site.

pair (E-R3, E-R4) was drilled with a separation of (6.09 m), approximately 20 m from (E-A, E-B), as shown in Fig. 3.

3. Core hydrogeophysical characteristics

Specimens from the cores were extracted for measurement of dc resistivity and dielectric response under varying moisture contents. West et al. (2001) showed that the relationship between bulk dielectric constant (κ_r) and moisture content (θ) for samples from the cores can be described using the complex refractive index method (CRIM)

$$\sqrt{\kappa} = (1-\phi)\sqrt{\kappa_s} + \theta\sqrt{\kappa_w} + (\phi-\theta)\sqrt{\kappa_a}, \tag{1}$$

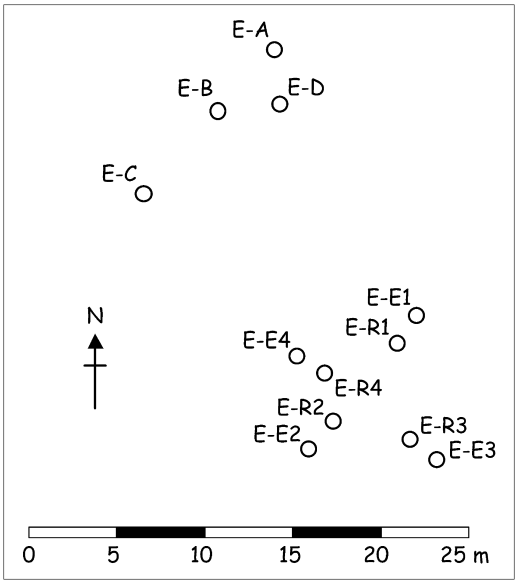

Fig. 3. Borehole layout at the Eggborough site.

where κ_s is the dielectric constant of the sediment grains, κ_w is the dielectric constant of water (assumed to be 81), κ_a is the dielectric constant of air (assumed to be 1) and ϕ is porosity. West et al. (2001) show that for 100 MHz frequency measurements a value of $\kappa_s = 5$ is appropriate for the main lithological unit present at both field sites (non-laminated medium grained sandstone).

In order to describe variation in dc resistivity with moisture content the empirical formula of Archie (Archie, 1942) was used

$$S = \left(\frac{\rho}{\rho_s}\right)^{-\frac{1}{m}}, \tag{2}$$

where S is saturation ($= \theta/\phi$), ρ is bulk resistivity, ρ_s is bulk resistivity at 100% saturation and m is an empirical constant.

Fig. 4 shows the measured saturation-resistivity response on three sandstone samples taken from the Hatfield core H-M, using natural groundwater as the saturating fluid. Using a least-squares fit to the data from the individual tests gives the following parameters: $m = 1.13 \pm 0.027$, $\rho_s = 65.84 \pm 4.36\ \Omega$m. Fig. 4 also shows the behaviour of Eq. (2) with the mean of the fitted parameters.

4. Field measurements and data analysis

Borehole-to-borehole radar surveys were conducted in zero offset profile (ZOP) transmission mode. In this mode, a radar signal is generated from a transmitter placed in one borehole with a receiver deployed in the other at the same depth as the transmitter. Measurement of the travel time of the received wave permits determination of the first

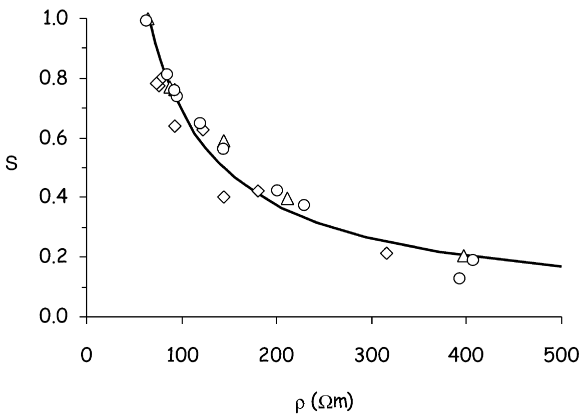

Fig. 4. Observed saturation (S)—dc resistivity (ρ) relationship from three sandstone samples from the Hatfield core. Different symbols indicate measurements on different samples. The solid line shows Archie's equation (Eq. (2)) with $m = 1.13$ and $\rho_s = 65.84$ Ωm.

arrival and hence velocity of the electromagnetic wave (v). By systematically lowering or raising the pair of antennae in the two boreholes, it is possible to build up a one-dimensional profile of travel time over the entire borehole length. In low loss materials and at high frequency, the bulk dielectric constant is derived from

$$\sqrt{\kappa} = \frac{c}{v}, \qquad (3)$$

where c is the radar wave velocity in air (≈0.3 m/ns).

Borehole-to-borehole radar measurements in ZOP mode were conducted at the Hatfield site between 1 February 1999 and 19 November 2000 at approximately monthly intervals. For all surveys the Sensors and Software PulseEKKO borehole radar system was used with 100 MHz borehole antennae. Surveys were conducted using 0.25 m intervals between antennae positions over the range 1–12 m below ground level. For all ZOP surveys a repeat set of measurements were made. Average, manually picked, first arrival travel time from the two measurements at each depth were used to determine variation in κ_r (and hence θ using Eq. (1)) with depth. A tracer test was carried out at the Hatfield site during February 1999, the results of which are reported in Binley et al. (2001a). Surveys carried out during February and March 1999 affected by the tracer test will not be recorded here, since the focus is the natural loading at the site.

At the Eggborough site, cross borehole ZOP profiles were conducted between 3 August 1999 and 19 November 2000. Again 0.25 m antennae spacing in the vertical was used, in this case to a depth of 16 m below ground level. High attenuation of the signal using 100 MHz antennae at a depth of approximately 5 m was observed between boreholes E-R3 and E-R4 (6.09 m apart). This can be attributed to the relatively high bulk electrical conductivity (typically 25–35 mS/m) observed at this depth from electromagnetic induction borehole logs. To overcome this attenuation, 50 MHz antennae were used for all surveys at the Eggborough site. The observed high attenuation at 5 m using 100 MHz antennae may indicate a restriction on the determination of absolute moisture contents directly from Eq. (1) due to likely uncertainty in κ_s at this depth. However, changes in moisture content will not be affected by such uncertainty, as shown later. A repeat survey was also carried out at the Eggborough site for each borehole pair and the average travel time at each depth used for determination of the dielectric constant.

Borehole resistivity surveys were made in borehole H-B at the Hatfield site using a Campus Geophysics Geopulse in a Wenner configuration. Using all 32 electrodes, this results in 29 measurements. Measurements in a reciprocal Wenner configuration were also made and an average of the [C+, P+, P−, C−] and [P+, C+, C−, P−] measurements were used as input for an inversion model to determine the vertical profile of resistivity. The resistivity surveys were carried out between 8 October 1998 and 14 December 2000 and, due to the location of borehole H-B, the results were not affected by tracer tests carried out at the site during this period.

In order to determine resistivity values from measured resistance profiles a regularised least-squares inversion approach was adopted. The vertical profile was discretised into layers 0.82 m thick and, using a finer discretisation for the numerical solution of the governing Helmholz equation, the resistivity for each layer was computed using an Occam's inversion (see for example, LaBrecque et al., 1996). For layers below 2 m depth (that is, representing the sandstone) Eq. (2) was used to convert resistivity values to moisture content θ, assuming a constant porosity of 0.32 (the average of Hatfield core sample estimates).

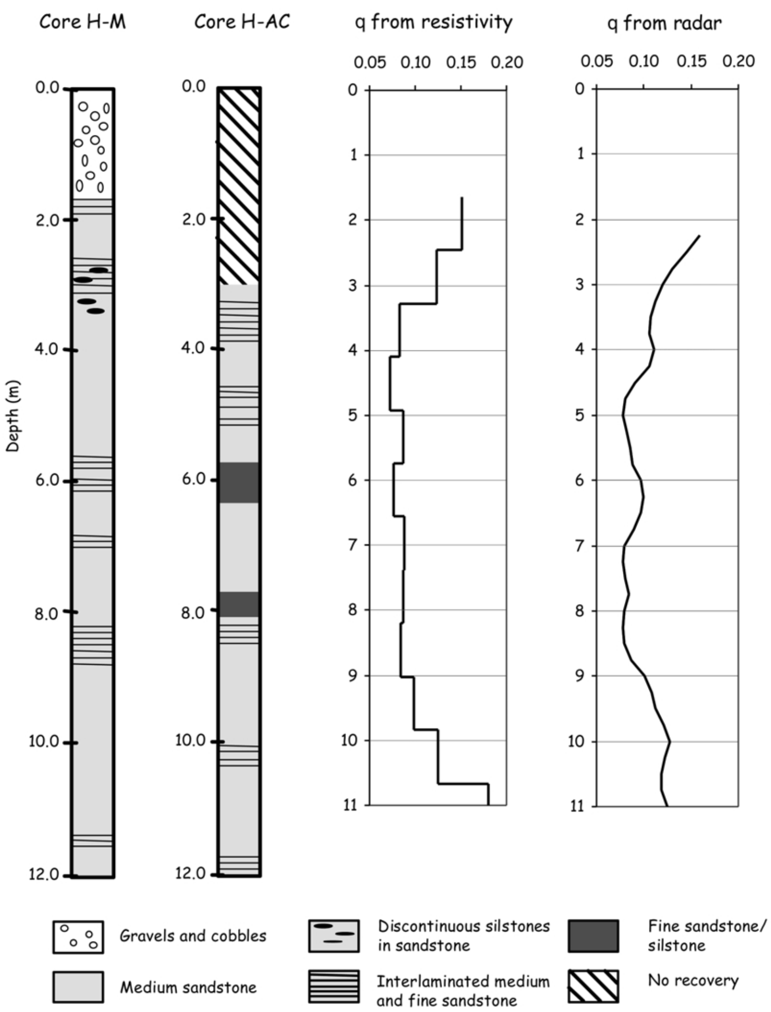

Fig. 5. Comparison of resistivity and radar derived moisture contents on 1 February 1999 at the Hatfield site together with the core lithological log.

5. Comparison of moisture content profiles derived from radar and resistivity at Hatfield

Fig. 5 shows a comparison of moisture contents derived from the radar and resistivity surveys on 1 February 1999 at the Hatfield site. Also shown in Fig. 5 are the lithological logs of the two Hatfield cores. A comparison of the core logs illustrates that the tops of the fine-grained units are not necessarily horizontal because these are erosional contacts. The logs do show, however, similar larger scale characteristics, see for example, the fine-grained units at approximately 6 and 8 m depth.

The two geophysically derived moisture content profiles in Fig. 5 show very similar patterns: a relatively high moisture content near the top of the sandstone, beneath which the moisture content is approximately 0.08–0.1, that is, a saturation of approximately 30%. The higher saturation near to the surface is likely to be a result of finer grained units (as shown in the core logs) impeding vertical flow of water. The moisture contents derived from the radar measurements show greater variation due to improved vertical resolution but also sensitivity of the bulk dielectric constant to lithological changes in the profile (as reported by West et al. (2001)) which has

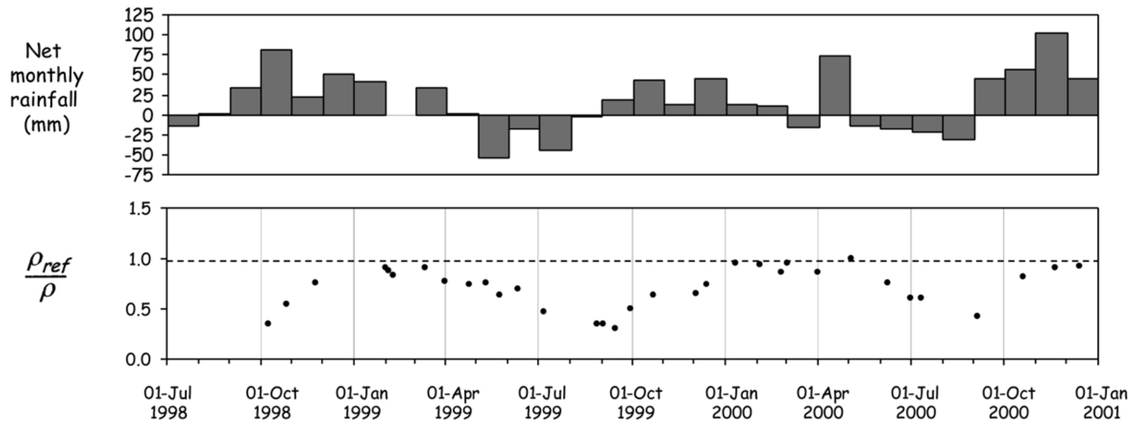

Fig. 6. A comparison of net monthly rainfall estimates and fractional change in electrical conductivity in 0–0.82 m layer relative to 3 May 2000. Net rainfall supplied courtesy of the UK Environment Agency.

not been accounted for here. The apparent increase in moisture content with depth between 9 and 10 m will be due to capillary effects close to the water table (at approximately 12 m depth). Note that application of Eq. (2) to determine moisture contents from resistivity measurements assumed that the pore fluid conductivity was the same as that of groundwater taken from boreholes at the site. Despite this, the resistivity and radar derived profiles show a remarkable similarity, in particular given the core log variability and that the radar and resistivity survey areas are approximately 50 m apart (see Fig. 2).

6. Changes in moisture content due to natural loading at the two sites

Daily rainfall, measured locally, coupled with actual evapotranspiration estimates (based on values from the UK Meteorological Office Rainfall and Evapotranspiration Calculation System—MORECS) have been used to compute monthly net rainfall figures prior to and over the monitoring period at the two sites. This has allowed a comparison to be made with inferred changes in moisture content using the two geophysical methods.

6.1. Resistivity and dielectric variation at the Hatfield site

Fig. 6 shows monthly net rainfall estimates at the Hatfield site for the period 1 July 1998–31 December 2000. Seasonal characteristics are the occurrence of main net inputs during September–January with a number of spring events during March or April, followed by relatively high recharge losses due to evapotranspiration during summer. The net rainfall during the 1998/1999 winter period is noticeably higher than that observed during the 1999/2000 winter. Also note the high input during October–November 2000, this particularly wet month resulted in extensive flooding locally and nationally.

Also shown in Fig. 6 is the change in the property:

$$\frac{\rho_{\mathrm{ref}}}{\rho},$$

where ρ_{ref} is the surface 0.82 m thick layer resistivity at Hatfield on 3 May 2000 and ρ is the resistivity of the same layer at each measurement date. Since electrical conductivity is the reciprocal of resistivity, this property is equivalent to fractional change in electrical conductivity. Although the reference date is arbitrary, 3 May 2000 was selected because; (a) moisture contents inferred from the datasets were typically stable in time during this period and (b) data were available at both Hatfield and Eggborough sites thus allowing a comparison of the behaviour of the moisture dynamics. The change in conductivity in Fig. 6 show a clear correlation with the net rainfall loading at the Hatfield site and a distinct similarity and symmetry is observed for the two full seasons monitored. The fractional change in conductivity

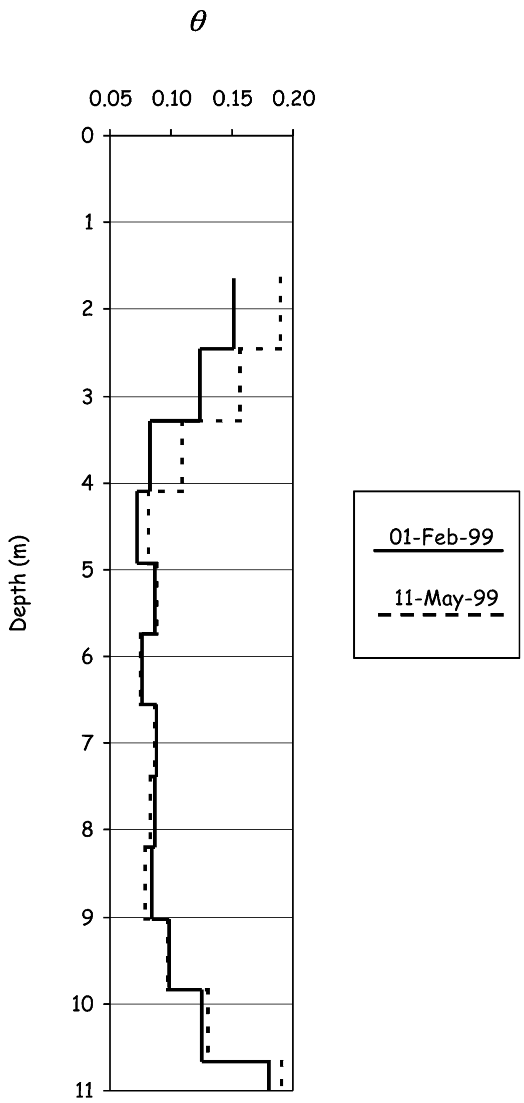

Fig. 7. Comparison of resistivity derived moisture content profiles on 1 February 1999 and 11 May 1999 at Hatfield showing propagation of the wetting front.

shows an increase starting during the month of September and continues to increase until a steady level is achieved during the months of January–March, which is followed by a steady recession during drier summer months. The change in conductivity mirrors the net rainfall and no noticeable time lag is observed between the two time series, as would be expected when considering the near surface soils.

As samples for petrophysical modelling were not obtained from the drift sediments it is not possible to convert the changes in resistivity in Fig. 6 to moisture content changes. This is possible, however, in the sandstone, that is, below 2 m depth. Using the Archie model in Eq. (2) changes in moisture content inferred from resistivity measurements may be estimated, as shown in Fig. 7. Here, moisture profiles are shown for 1 February 1999 and 11 May 1999. The vertical migration of a wetting front is clearly seen down to a depth of 5 m over this 3 month period. More instructive is a comparison of changes in moisture content at specific depths. Fig. 8 shows such changes computed for depths from 3.28 to 9.02 m. Maximum changes in moisture content at depths over 4 m are of the order of 2%. Despite such small changes the propagation of wetting and drying fronts can be distinguished. Arrows in Fig. 8 show approximate times of the onset of increased moisture content due to the 1998/1999 winter recharge. In Fig. 6 the onset of increased moisture content in the upper layer due to the 1998/1999 winter recharge is estimated to occur early in September 1998. In Fig. 8 increases in the 3.28–4.10 m deep layer occur early in March 1999 and is thus delayed by approximately 6 months over the top 3–4 m. This is equivalent to an effective wetting front velocity of approximately 0.5 m per month through the drift and upper sandstone. In contrast, increased moisture content in the 8.20–9.02 m deep layer occurs approximately mid-May 1999. This equates to propagation of the front at approximately 2 m per month through the sandstone. These travel times do not indicate directly the likely advective transport rate of any contaminants applied to the surface since variation in water content may be governed by pressure wave propagation through the system. Nevertheless, the observed data offers a useful starting point for the development of hydraulic models of unsaturated flow, which will underpin any contaminant transport model.

Resistivity will not only be a function of moisture content but also the electrical conductivity of the pore water. In the above analysis it is assumed that the pore water conductivity does not change over time. This may restrict the use of resistivity profiling for moisture content determination, although it is likely that pore fluid conductivity variation is only significant in the top few metres of a profile. Such variation is expected due to changes in temperature and

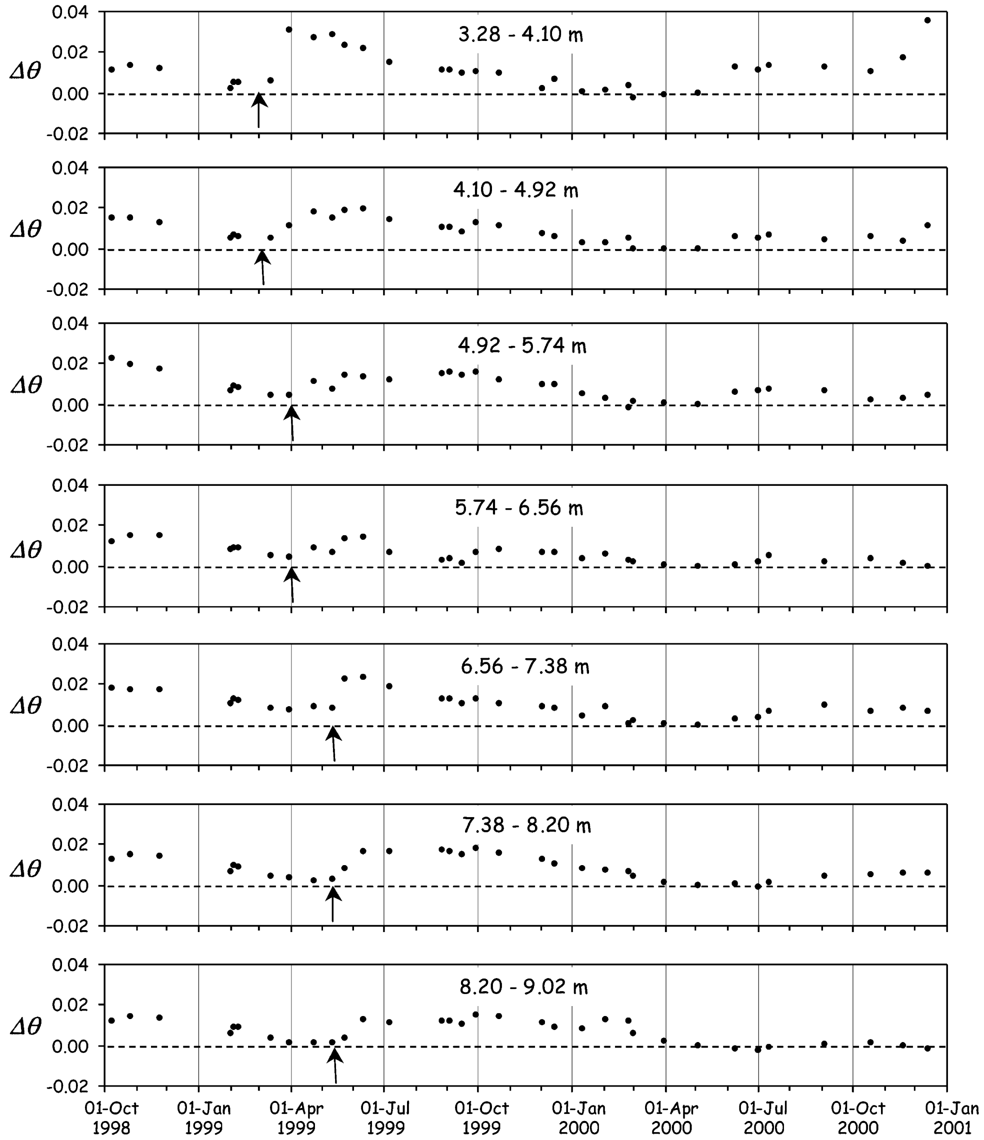

Fig. 8. Change in moisture content at the Hatfield site over selected intervals using resistivity estimates. All differences are relative to 3 May 2000. Arrows indicate estimated time of rise in moisture content in 1999.

bacterial production of CO_2 in the soil that then results in mineral dissolution by carbonic acid. Radar velocity profiles, in contrast, should not be affected by changes in conductivity of the pore water and thus provide a useful comparative technique.

West et al. (2001) have shown how the dielectric constant for the sediment grains varies with lithology for the radar frequencies used here. Determination of absolute moisture content using such methods may then be sensitive to these parameters (see Binley et al., 2001a). Changes in saturation, using the CRIM model in Eq. (1), however, are insensitive to the dielectric constant of the sediment grains since the change in volumetric moisture content is given by

$$\Delta\theta = \frac{\sqrt{\kappa^t} - \sqrt{\kappa^0}}{\sqrt{\kappa_w} - \sqrt{\kappa_a}}, \quad (4)$$

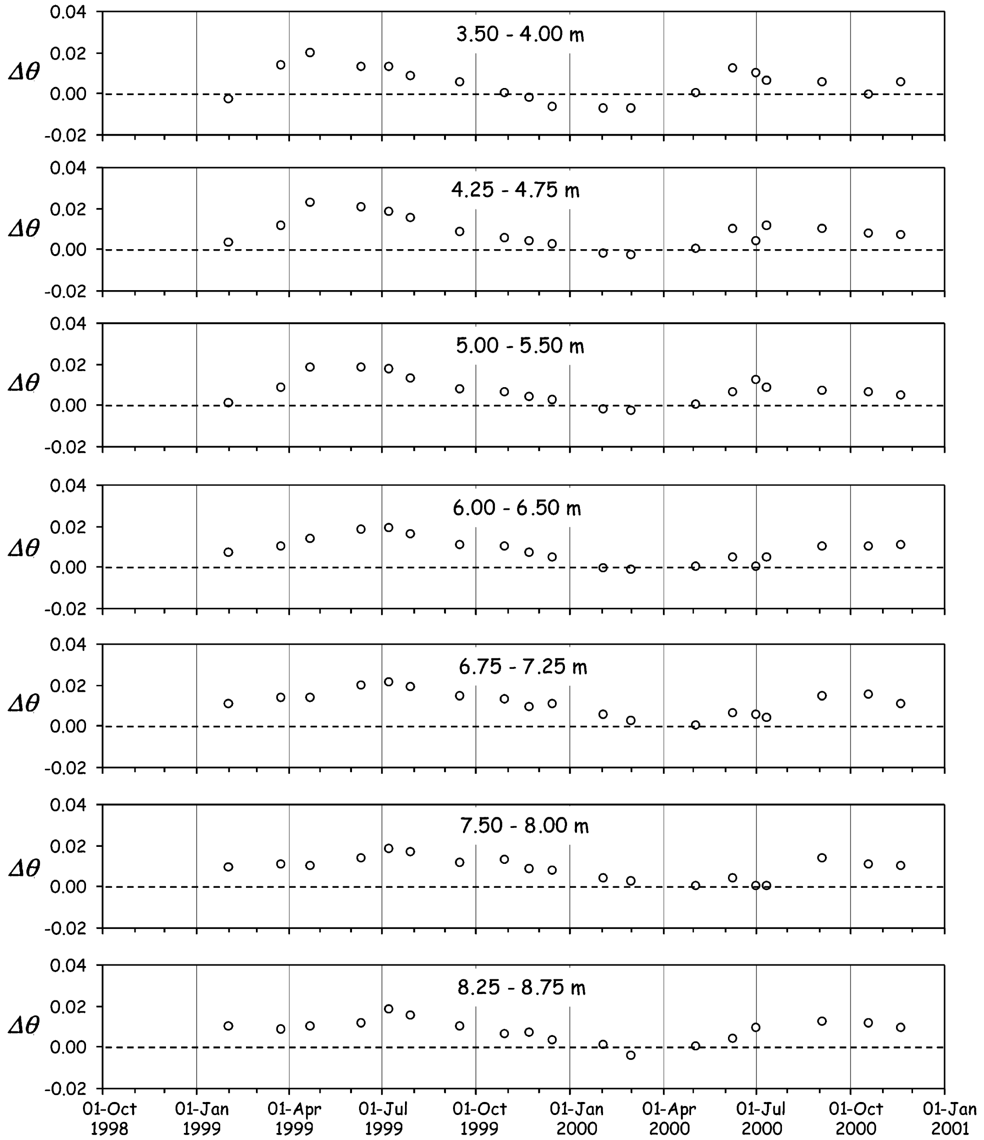

Fig. 9. Change in moisture content at the Hatfield site over selected intervals using radar estimates. All differences are relative to 3 May 2000.

where κ^t is the bulk dielectric constant at time t and κ^0 is the background (reference) bulk dielectric constant.

Using Eq. (4), with 3 May 2000 as the reference date, changes in moisture content at selected depths were computed. Fig. 9 shows the results using 0.75 m interval averages, in order to compare with the resistivity derived results in Fig. 8. Note that the vertical scales used in Figs. 8 and 9 are identical. The radar time series show a clear correlation with the resistivity-computed series, both in terms of the magnitude and timing of moisture content changes. The radar results show slightly less scatter than the resistivity derived profiles, which is perhaps a reflection of; (a) the larger sampling volume of the radar measurements and (b) the fact that the resistivity based estimates are computed following a model fit to the field resistance profile data. Given that the radar and resistivity surveys were made 50 m apart there is a striking similarity in pattern and magnitude of computed changes.

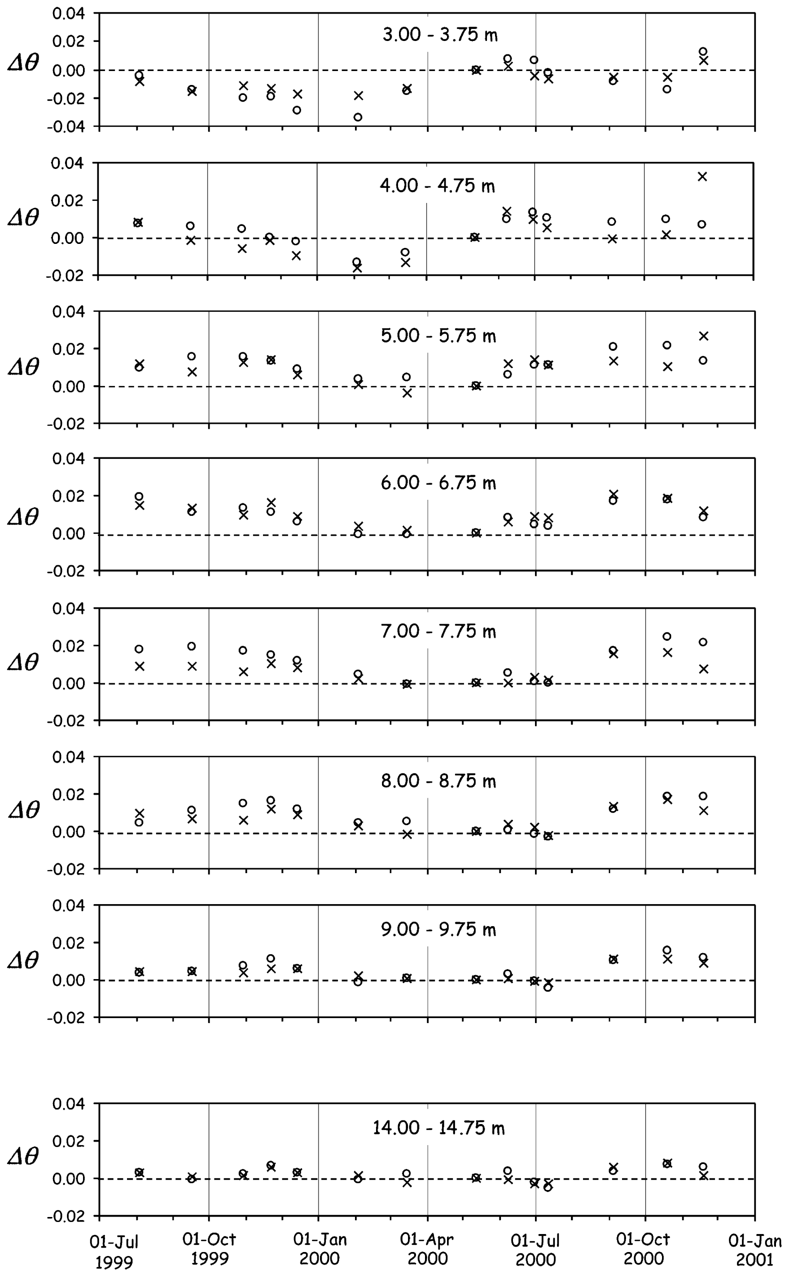

Fig. 10. Change in moisture content over selected intervals at the Eggborough site for borehole pairs E-A, E-B (open circles) and E-R3, E-R4 (crosses). All differences are relative to 12 May 2000.

6.2. Dielectric variation at the Eggborough site

Zero offset radar profiles carried out at the Eggborough site allow a comparison to be made between two localities (17 km apart) with similar sandstone lithology. Fig. 10 shows computed changes in moisture content at selected depth intervals for the two borehole pairs (E-A, E-B) and (E-R3, E-R4).

These borehole pairs are approximately 20 m apart, however, the observed changes show much similarity. Most variation between the two plots occurs between 4 and 6 m depth, which is likely to be a result of relatively high attenuation in this interval as noted earlier. This effect will be particularly significant during increased saturation. At depths greater than 6 m, the maximum variation in moisture content over the 17 month period is seen to be approximately 2%, which is comparable to those changes observed at the Hatfield site (Fig. 9). The Eggborough series is unfortunately too short to make reliable computation of wetting and drying front propagation times but by comparing the observed series in the 5.0–5.75 m deep layer and the 9.0–9.75 m deep layer an estimate is possible. In the 5.0–5.75 m deep layer the onset of increased moisture content in summer 2000 occurs during April/May, whereas in the 9.0–9.75 m deep layer this onset is shifted by approximately 2–3 months. Over this 4 m interval in the sandstone this is equivalent to a transmission rate of approximately 1.3–2 m per month. Note that this is similar to the observed transmission rate at the Hatfield site.

It is also apparent from Fig. 10 that the observed electrically conductive layer at a depth of 5 m acts as a resistance to flow since the velocity of the wetting front in 2000 is significantly greater in the upper depth intervals, again as noted at the Hatfield site. Fig. 10 also shows changes in moisture content over the interval 14–14.75 m. Note here that at both field plots the maximum changes of approximately 0.5–1% are seen, suggesting reasonably high sensitivity of the radar profile approach.

The results from Eggborough serve as a means of generalising the Hatfield results for similar sandstone lithologies and perhaps add support for generalised models of unsaturated flow in this area.

7. Conclusions

Using petrophysical relationships derived from core scale measurements moisture content profiles determined from single borehole resistivity surveys and cross-borehole GPR transmission surveys have been compared at a Sherwood Sandstone field site. Similar patterns of moisture content throughout the unsaturated thickness were observed. Through repeated measurements of these two survey methods the moisture dynamics in the unsaturated zone have been determined. Computed time series at various depths throughout the profile show strikingly similar temporal behaviour. At depths greater than 5 m the maximum variation in moisture content is typically 2%. The results show a lagged response due to natural loading on the surface. At depths of 3 m (that is, near the top of the sandstone) the onset of a rise in moisture content appears to lag 6 months behind start of winter rainfall inputs. This wetting front propagates through the sandstone at approximately 1.3–2 m per month.

Similar borehole radar profiles were obtained from repeated measurements using two borehole pairs at a second field site. The computed wetting front time series at both field sites compare favourably in terms of maximum observed changes and vertical propagation rates. At the second site changes in moisture content between 0.5 and 1% at depths of 14–15 m were noted, suggesting reasonably high sensitivity of the radar profile approach. The relatively small changes observed throughout the main profile would not be detectable from surface applied geophysical surveys.

Changes in moisture content do not reveal directly the travel times of solutes through the profile but may serve as useful data for constraining hydraulic models of unsaturated flow, which in turn will serve to underpin contaminant transport models. Research is currently underway to achieve this goal with a view to improving regulatory models applied to this nationally important aquifer.

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