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Electrical Imaging of Saline Tracer Migration for the Investigation of Unsaturated Zone Transport Mechanisms.

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Abstract

Better understanding of field-scale unsaturated zone transport mechanisms is required if the fate of contaminants released at the surface is to be predicted accurately. Interpretation of results from direct tracer sampling in terms of operative hydraulic processes is often limited by the poor spatial coverage and the invasive nature of such techniques. Cross-borehole electrical imaging during progress of saline tracer migration is proposed to assist investigation of field-scale solute transport in the unsaturated zone. Electrical imaging provides non-destructive, high density and spatially continuous sampling of saline tracer transport injected over an area of the ground surface between two boreholes. The value of electrical imaging was tested at a field site on an interfluve of the UK Chalk aquifer. Improved understanding of active transport mechanisms in the unsaturated zone of the UK Chalk is required to predict its vulnerability to surface pollutants.

In a tracer experiment in May 1996, a conductive saline tracer was infiltrated over 18 m^2 at an average rate of 47 mm day^{-1} for 56 hours. Cross-borehole images obtained during and after infiltration show a large, homogenous, resistivity reduction in the top 3 m, no change between 3 m and 6 m depth, and smaller, inhomogeneous, resistivity reductions below 6 m depth. The resistivity has reduced at down to 15 m depth less than 2 days after tracer infiltration began. Hydrological interpretation of a sequence of electrical images obtained prior to, during, and up to three months after tracer injection suggests: (1) rapid tracer entry into the soil zone and upper 2 m of weathered Chalk, (2) intergranular transport of the bulk of the tracer, (3) a significant fissure flow component transporting tracer to at least 15 m depth in 31 hours, and (4) vertical changes in transport mechanisms possibly caused by interception of fissures by marl layers. The results of this experiment suggest that electrical imaging can assist the description of unsaturated zone hydraulic mechanisms through visual identification of spatial and temporal variations in transport processes.

Introduction

CHARACTERISATION OF SOLUTE TRANSPORT IN THE UNSATURATED ZONE.

The development of methods to improve understanding of downward solute transport mechanisms through the unsaturated zone has been a priority of hydrologists for many years. Increased awareness of the vulnerability of groundwater resources to surface-derived contaminants has emphasised the need for new methods in this field. Surface sources of contamination include chemicals released from (1) industrial process sites, and (2) landfills. Fertiliser and pesticide application resulting from intensive agricultural land use also contributes to the chemical loading of the unsaturated zone. The unsaturated zone acts as a natural barrier between the surface and groundwater aquifers. Consequently, the fate of contaminants currently in transit within the unsaturated zone (as determined by operative transport mechanisms) is of political, economic and social concern.

Investigation methods of contaminant transport include (1) field studies around identified pollutant sources, (2) laboratory tests, and (3) *in situ* tracer experiments (Williams and Higgo, 1994). The value of the first approach is often limited by poor knowledge of the quantity and mechanism of contaminant release. Laboratory tests require that aquifer material be sampled and transported to the laboratory: during these operations physical disturbance of the samples may occur. In addition, the scale of laboratory measurements may be too small to be representative of field scale transport processes. *In situ* tracer experiments allow natural conditions to be maintained and the injection of solute to be controlled. *In situ* tracer experiments involve the application of a tracer at the surface followed by subsurface sensing of variations in the quantity of tracer in time and space, from which solute transport characteristics are inferred.

In field scale tracer tests, the movement of surface applied tracer through the unsaturated zone is often determined from soil solution sampling or soil coring (see for example, Black and Kipp, 1983; Jury and Sposito, 1985; Ellsworth *et al.*, 1991; Jabro *et al.*, 1994). The limitations to this approach are well recognised. Soil sampling on a grid over the study site is both expensive and time consuming. Soil coring is destructive and can cause disturbance to the natural transport processes being monitored. A fundamental limitation is that the spatial distribution of the tracer may be poorly defined from such 'point measurement' methods. The concentration of tracer between sampling points must be predicted by interpolation between measurements. Given that heterogeneity is the rule rather than the exception, interpolation between sampling points can be dangerous. In particular, preferential tracer transport via localised hydraulically conductive pathways may not be intercepted by the sampling grid. Examples of preferential transport pathways include (1) fractures/fissures in rock, and (2) sand lenses in clay.

Ellsworth and Jury (1991) note that vertical heterogeneity in particular introduces significant problems into the description of solute transport. They state that, 'behaviour of the solute at the interface between layers can have a significant effect on large scale behaviour by, for example, increasing lateral mixing or terminating preferential flow channels'. Although increasing the density of sampling points can improve characterisation of aquifer heterogeneity, the expense and time required also increases. Alternative methods which can define the spatial distribution of transport mechanisms are hence required. The recent development of modelling techniques based on stochastic approaches emphasises this need. These approaches require the characterisation of subsurface hydraulic properties in terms of probability distributions and have much greater data demands in comparison with conventional modelling methods.

THE GEOPHYSICAL APPROACH TO GROUNDWATER INVESTIGATION

Geophysical sensing methods allow the estimation of earth properties (such as density, resistivity and magnetic susceptibility) from measurements made using instruments placed at the surface or in a borehole. Geophysical methods are relatively non-invasive and, by moving instruments across the surface or along a borehole, allow the subsurface distribution of an earth property to be mapped. The success of a geophysical method in a groundwater investigation depends on the degree to which the sensed earth property is a function of hydrological variables. As hydrological information is sensed indirectly, considerable care is required in interpretation. Examples of the successful application of geophysical methods to groundwater issues are comprehensively detailed in Kelly and Mareš (1993).

The electrical resistivity method is the most frequently used geophysical technique in hydrology as the resistivity of the ground depends strongly on the effective porosity, degree of saturation and pore water conductivity. The method involves driving a known electric current between two electrodes and measuring resulting potential differences between other pairs of electrodes. A transfer resistance to electric current flow (defined as the ratio of the measured voltage to applied current) is calculated. The changes in resistance observed from electrode grids at the surface are recorded and interpreted in terms of the direction and velocity of tracer migration in the saturated zone (White, 1988; Osiensky and Donaldson, 1994). Kean *et al.*, (1987) describe the use of a surface electrode array from which changes in resistance were correlated with changes in moisture content in the unsaturated zone.

ELECTRICAL IMAGING

Electrical imaging, or Electrical Resistivity Tomography (ERT), refers to the automated collection of a large number of resistance measurements from which an image of the resistivity distribution of the investigated medium is reconstructed. Given the dependency of resistivity on the hydrogeological variables described above, electrical imaging may be an effective method for investigating field scale transport processes in heterogeneous media. Binley *et al.* (1996) describe the location of preferential flow pathways in soil cores using electrical imaging: destructive dye staining confirmed the location of these pathways.

Andrews *et al.*, (1995) used a surface array to perform field scale electrical imaging at sites on the unsaturated zone of a chalk aquifer. They attributed variations in lateral resistivity to discrete sand lenses believed to represent preferential drainage routes for surface infiltration. As a consequence of the increased distance from the electrodes used to inject current, the resolution of electrical imaging using surface arrays is reduced at depth. Although this may not be a major limitation to the imaging of a lateral resistivity structure, imaging of a vertical structure, such as the vertical transport of a tracer through the unsaturated zone, is complicated by this variable resolution.

Cross-borehole electrical imaging involves the use of electrodes placed within boreholes. Numerous between-borehole resistance measurements are used to reconstruct the resistivity of the between-borehole medium. In the resulting image, the resolution of resistivity structure is maintained at depth. The concept of cross-borehole electrical imaging of unsaturated zone hydraulic processes was demonstrated by Daily *et al.*, (1992). They monitored the vertical migration of moisture through 20 m of fluvial and lacustrine sediments and showed that changes in resistivity were a good indication of moisture migration. Another recently reported hydrological application of cross-borehole electrical imaging is the identification of hydraulically conductive fractures in a limestone aquifer (Slater *et al.*, 1997). In both these studies, the reconstruction of images of resistivity change caused by tracer migration was shown to provide useful hydrological information.

The concept of field scale cross-borehole electrical imaging as a method of investigating transport mechanisms in heterogeneous media is illustrated in Fig. 1. An electrically conductive (saline) tracer is injected at the surface. Progress of this tracer through the subsurface changes both (1) the saturation, and (2) the pore water resistivity, of the material affected by the tracer. Reconstruction of the resistivity changes between an image during tracer injection and an image prior to tracer injection reveals the spatial tracer distribution. From the observed tracer distribution, operative transport processes are inferred. Repeated imaging over time allows temporal changes in transport processes to be identified.

The objective of this paper is to demonstrate the potential hydrological value of field-scale cross-borehole electrical imaging for the investigation of solute transport mechanisms in the unsaturated zone. The study site is on the UK Chalk aquifer where much interest in the hydraulics of the unsaturated zone exists.

Hydraulics of the unsaturated zone of the UK Chalk aquifer

Water quality in the UK Chalk aquifer has deteriorated over the last three decades due to anthropogenic activities. In particular, nitrate levels in many abstractions have increased due to intensive fertiliser application on the arable land that makes up much of the Chalk outcrop (Foster and Crease, 1974). New threats to the Chalk aquifer include pesticides (Foster *et al.*, 1991), and hydrocarbons such as petroleum products and chlorinated solvents leaking from tanks and pipelines (Lawrence and Foster, 1987).

Over extensive areas the Chalk aquifer has an unsaturated zone more than 10 m thick and, at some locations, more than 50 m thick (Foster, 1993). This zone is a natural first defence against contamination of groundwater. The need to predict future pollutant (particularly nitrate) levels in groundwater supplies has stimulated much work to investigate the transport mechanisms operative in the unsaturated zone. Interpretation of flow mechanisms from

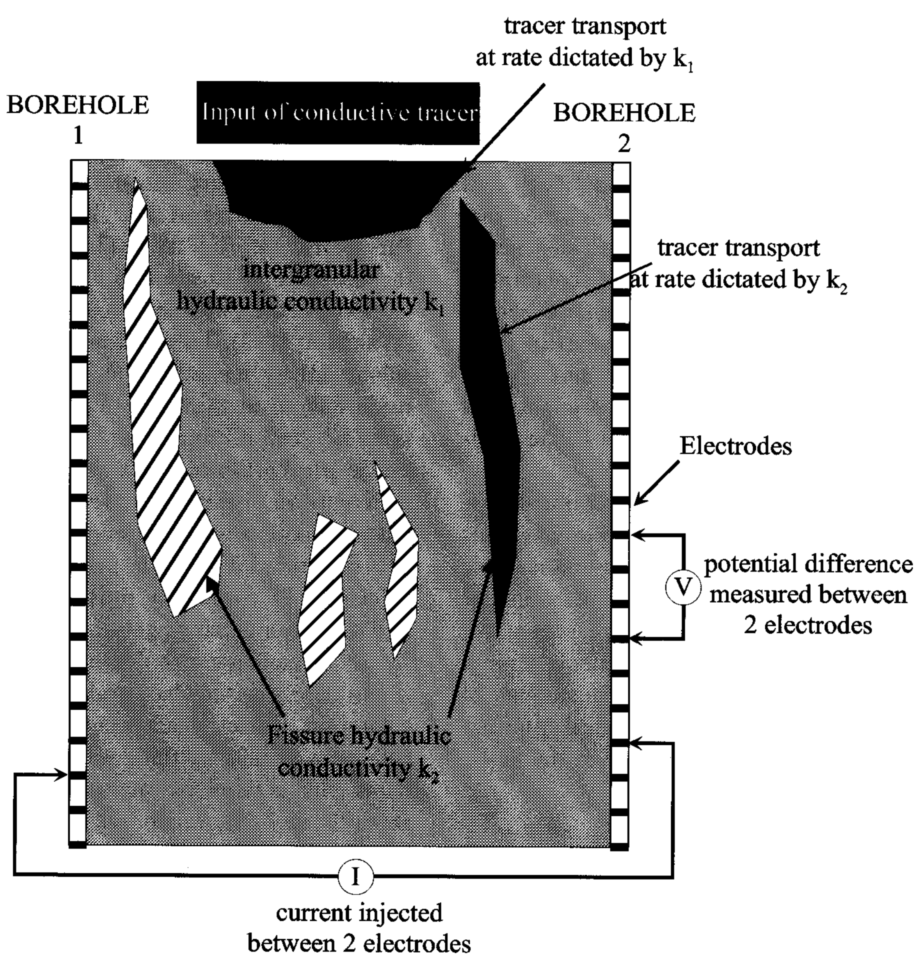

Fig. 1 *Concept of cross-borehole imaging illustrated for a hypothetical dual hyraulic conductivity media.*

the results of field studies has been the subject of considerable uncertainty and controversy (Geake and Foster, 1989). In particular, much debate has centred on the degree to which transport in the unsaturated zone occurs via macrofissure 'by-pass' flow mechanisms.

In previous work, Chalk unsaturated zone behaviour has been investigated using stable and radioactive isotopes, nitrate profiles, tracer studies and physical measurements of fluxes, suctions and moisture content. Physical measurements at a site on the Upper Chalk in Hampshire (Wellings and Bell, 1980; Wellings, 1984) showed that most flow was relatively slow (less than 1 mm day^{-1}) with rapid flow through macrofissures occurring only during periods of exceptionally high infiltration. Analysis of pore-water thermonuclear tritium profiles at sites in Berkshire, Dorset and Norfolk (Foster and Smith-Carrington, 1980) also indicated mainly slow flow rates, although mass balance calculations showed that up to 20 % of tritium had been lost from the unsaturated zone, probably via a rapid 'by-pass' flow mechanism.

Although the studies mentioned above show that solute transport through the Chalk unsaturated zone is slow in some areas, the lithological and fracture characteristics of the UK Chalk are highly variable. Rapid transport of solutes to the water table is likely in areas of high fissure hydraulic conductivity (Gardner *et al.*, 1990), for example where the Chalk displays karstic features (see Banks *et al.*, 1995). Studies of unsaturated flow characterisation by analysis of stable isotope profiles (Darling and Bath, 1988) and tracer tests on instrumented field plots (Black and Kipp, 1983; Barraclough *et al.*, 1994) have confirmed that solute transport behaviour is site specific and dependent on infiltration rate and antecedent ground conditions. Indeed, Foster (1993) states that, 'the fact that the behaviour of a contaminant in the unsaturated zone can vary very widely with external hydraulic loading and type of chalk, cannot be overemphasised'. Hence, there is a need to characterise unsaturated zone behaviour at the individual catchment scale.

Conductive tracer studies in the Chalk unsaturated zone using cross-borehole electrical imaging are reported in this paper. The results reported here are from cross-borehole imaging of a tracer experiment performed in the summer of 1996, although reference is made to a previous tracer experiment and various surface and cross-borehole surveys conducted between the winter of 1994 and the summer of 1996. The study shows that useful hydrological information is obtainable from the unsaturated zone of the Chalk using electrical imaging.

The study site

LOCATION

The field site is located on West End Farm, Kilham, East Yorkshire (Fig. 2, inset). It is within an area of arable farmland on a topographical spur in the Chalk above the intersection of Langtoft Valley and Broachdale (Fig. 2). The unsaturated zone is about 80 m thick at this site. Water from a public supply abstraction (Kilham Pumping Station), located about 1200 m away and 60 m below the field site at the intersection of the valleys, has shown steadily rising nitrate levels over the past decades. Its nitrate level is approaching the EC drinking water limit of 50 mg l^{-1} NO_3^{2-} and may exceed it in the near future.

The catchment area of Kilham pumping station was one of ten pilot areas designated Nitrate Sensitive Areas (NSA) in July 1990 following The Water Act of 1989. The boundary of the NSA is shown in Fig. 2; as flow models have suggested an unsaturated zone component of recharge, this includes the interfluvial spur (J. Aldrick, 1996, pers. comm.). Nitrate levels in the pumped supply have remained high since the introduction of the NSA scheme in 1990, indicating a substantial nitrate reservoir remaining within the unsaturated zone. Until the behaviour of the unsaturated zone is understood, the effectiveness of NSA imposition cannot be predicted.

GEOLOGY

Based on the classification of Wood and Smith (1978), the Chalk in the Kilham area falls within the Flamborough Chalk Formation of Senonian age, which corresponds broadly to the Upper Chalk of Southern England. The Sewerby Member probably outcrops at the field site (F. Whitham 1996, pers. comm.) as this is exposed locally at Nafferton Wold (grid ref. TA 0475 6130) and Ruston Parva (grid ref. TA 06956135). The nearest exposure to the field site at Lowthorpe Quarry, Ruston Parva shows massive bedding with marl bands at around two per metre (Whitham, 1993). These marls are silty and of grey/brown colour and are generally around 0.01 m thick, though some reach 0.06 m in thickness. The spacing of joints is likely to be between 0.7 and 1 per m as observed in other quarries in the Yorkshire Chalk (Foster and Milton, 1976).

Percussion drilling to between 2 and 3 m using a 38 mm diameter bore was carried out at two locations on the field site in June 1996. Both percussion boreholes (Fig. 3) revealed 0.25 m of silty topsoil consisting of quartz and chalk, containing chalk gravel fragments which increase in size and frequency with depth. Below the topsoil is a horizon of poorly sorted chalk gravel, showing mottled red discoloration. Intact chalk containing discontinuous marl bands up to 0.02 m thick was found below about 0.8 m depth. Its gravimetric moisture content varied between about 9 and 18 %, which was higher than that of the overlying soil.

Buckley and Talbot (1996) report downhole resistivity and gamma ray measurements taken in February 1996 from a 100 m deep borehole at the site. These reveal the presence of prominent marl bands at 12 m, 16 m, 40 m, 43 m and 70–74 m depth; these may be up to four times

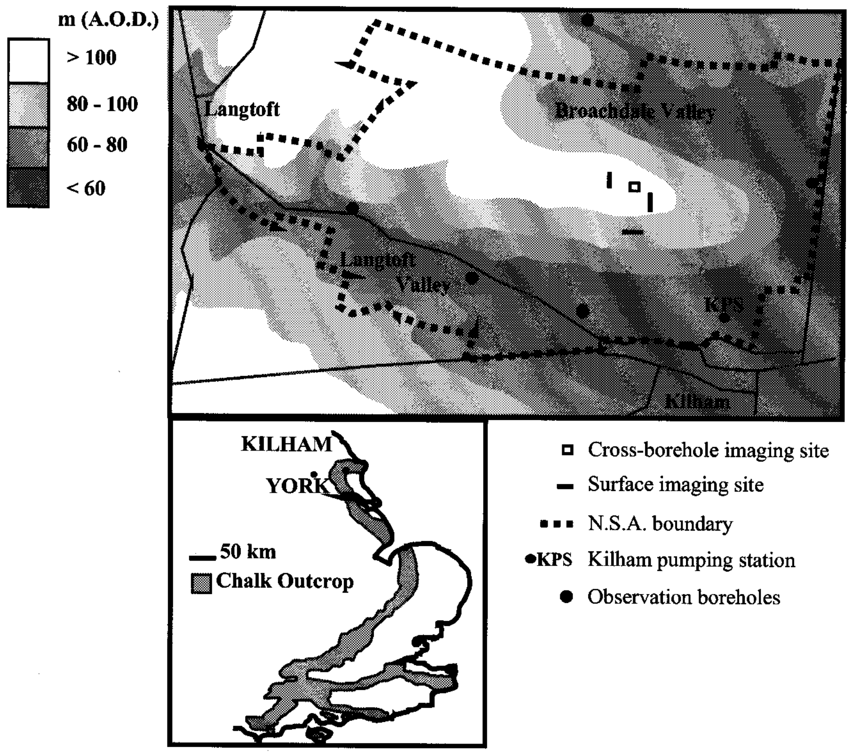

Fig. 2 *Location of field site, Kilham, East Yorkshire. Inset: location of Kilham on outcrop of UK Chalk aquifer.*

thicker than those seen in the shallow percussion boreholes. The resistivity in the unsaturated zone is mostly around 150 Ωm, but is lower (down to 50 Ωm) in the vicinity of these prominent marls. Downhole resistivity and gamma measurements at nearby observation boreholes (Fig. 2) indicate that prominent marl bands are extensive laterally in the Kilham area (J. Aldrick 1996, pers. comm.). Marl bands in limestone lithologies are often hydrological barriers which lead to perched water tables in the unsaturated zone. However, Foster and Milton (1976) argue that, in the Yorkshire Chalk, vertical or inclined fractures traverse these marls frequently enough to ensure vertical flow and prevent formation of local perched water tables.

HYDROMETEOROLOGY

MORECS data for 1985 to 1996 were used to provide a tentative estimate of the bulk recharge for the Kilham area. The average annual rainfall for the Kilham area is approximately 650 mm and the average value of actual evaporation over the same period is 400 mm, resulting in an annual bulk recharge of about 250 mm, mostly from winter drainage (although this estimate is quite low in comparison with other estimates presented in the literature). Rainfall intensities in excess of 20 mm day^{-1} are often recorded at Leaconfield Meteorological Station (40 miles south and only 6 m above mean sea level) between the months of September and March and the highest loading recorded in the last five years was 35 mm day^{-1} . High magnitude events are not confined to the winter months; 31 mm of rainfall were recorded in 24 hours on June 4 1995, representing nearly 70 % of the total average rainfall for that month. The return period of such events has not been calculated. The intergranular permeability of Kilham Chalk is only 3×10^{-9} m^2 (B. Clennell 1995, pers. comm.) corresponding to a maximum hydraulic conductivity of 0.3 mm d^{-1}. At a catchment scale, the delay between storm events and rise in the water table may be as small as twenty days (Barker *et al.*, 1983), which indicates fissure flow in the unsaturated zone (although this

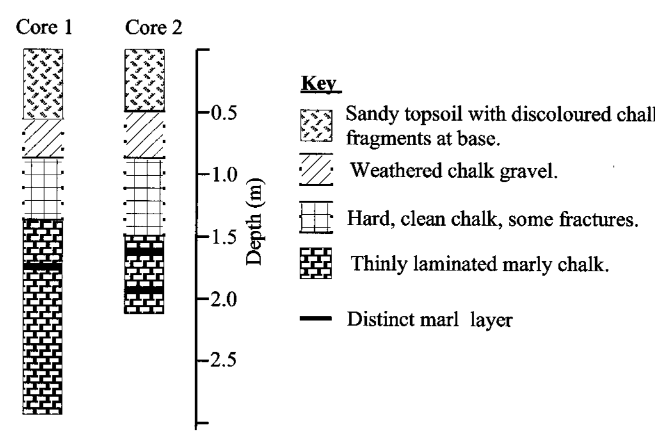

Fig. 3 *Core-logs obtained from percussion drilled boreholes.*

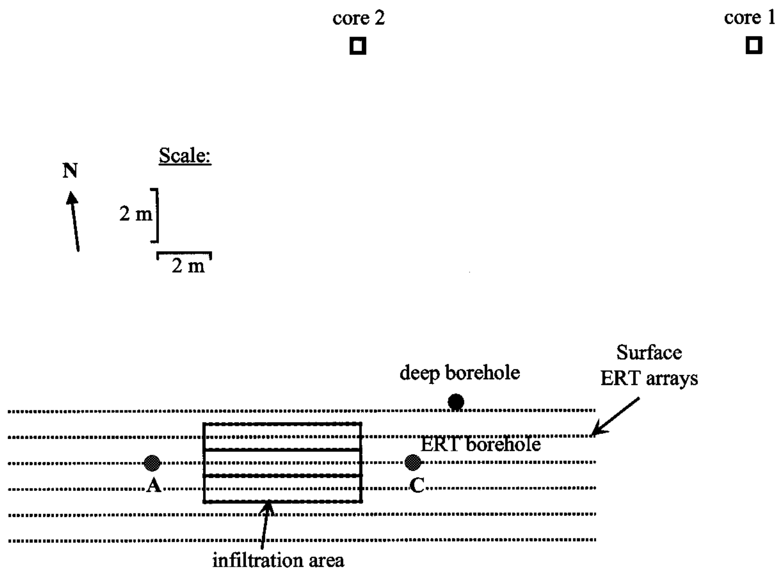

Fig. 4 *Plan of cross-borehole measurements made at three times prior to tracer injection.*

rapid recharge is probably mainly via the thin unsaturated zone in the valleys).

Electrical image reconstruction

Cross-borehole ERT image reconstruction involves the determination of the resistivity structure between boreholes from the resistance measurements made using electrodes placed down boreholes (Fig. 1). A single ERT data set consists of a large number (typically several hundred) of measurements of resistance, thus requiring a computer-controlled data acquisition system. Given these measurements the resistivity distribution is determined by suitable inverse methods. The goal of the inversion is to compute an optimal set of parameters, each of which is a resistivity value of a pre-defined block, the complete set of such blocks making up the entire between-borehole region. Here 'optimal' refers to minimisation of an objective function which includes a component that measures the fit between measured data and modelled values. The objective function also includes a component which minimises image roughness to prevent geologically unrealistic solutions. Resistivity modelling (the computation of theoretical resistance measurements given a set of known block resistivity values) is performed using the finite element method.

Data weights are used to assign confidence levels to measured resistance values for the inversion process. Measurement errors can arise from a number of sources: poor electrical contact at measurement electrodes is the commonest source of error in cross-borehole electrical imaging. Hence, quantification of data weights is critical to a determination of a statistically meaningful image. Binley *et al.*, (1995) have suggested that the reciprocal error is a suitable characterisation of ERT data quality: the switching of current and potential electrodes should provide the same resistance value and deviations from this give an error quantification. Thus, measurements which do not reciprocate well are weighted less than those that have low reciprocal errors. The image reconstruction procedure is described in detail by LaBrecque *et al.*, (1996).

Site Instrumentation

Two boreholes (0.1 m diameter) were drilled using an air flush open hole rotary method in the positions shown in Fig. 4 (boreholes A and C). An electrode array, manufactured from 3 m lengths of flexible plastic pipe, was installed in each borehole. The arrays were positioned so that the uppermost electrode was 0.5 m below the ground level. Each array contained 20 electrodes spaced at 0.75 m intervals. The holes were back-filled with powdered chalk obtained from a local quarry. Electrical measurements in a trial borehole had shown that good electrical contact with the Chalk could be obtained using the powdered chalk.

A suitable measurement protocol (set of four electrode resistance measurements) was selected by prior synthetic modelling. Several protocols were tested for sensitivity to a vertically migrating, conductive contaminant plume invading from the surface mid-way between the boreholes. An increased number of measurements improves the image resolution but at the expense of increased data set collection time. Monitoring a changing resistivity distribution due to tracer movement requires that the system can be considered essentially static over the time taken to collect the data set. The selected protocol consisted of 1000 measurements of which 500 were reciprocals measurements for error analysis. A single image frame required about two and a half hours to collect, which was acceptable for data set collection every 24 hours.

Additional electrical imaging using surface electrode arrays was performed to characterise the resistivity structure at selected sites across the interfluve (restricted to regions where access to land had been granted), and to monitor control sections during the tracer test in case of rainfall (in fact no rainfall occurred over the infiltration period). Electrode arrays with a 2 m electrode spacing were used, giving a maximum investigation depth of about 10 m.

Tracer Injection

Tracer injection was performed in May 1996 using an irrigation array consisting of plastic pipe with adjustable taps spaced at 0.25 m intervals. The tracer was NaCl at a concentration of 60 g l^{-1}, with a conductivity of 8 S m^{-1}. The pipe was laid out to cover a 6 m by 3 m area centred on the cross-borehole image plane (Fig. 4). The array was fed from a 200 litre header tank in which a constant head was maintained via a pipe from a bowser. The taps were set to release on average 35 litres per hour over an 18 m^2 area, resulting in an average infiltration rate of 47 mm day^{-1}. This rate was as large as possible whilst remaining representative of a credible rainstorm. Tracer was input for a period between 09:00 on 14/05/96 and 17:00 on 16/05/96, resulting in a total tracer volume of approximately 1960 litres. At no time during tracer injection was ponding at the ground surface observed, though some of the tracer may have been lost to the ground outside the infiltration area.

An earlier tracer injection experiment had been carried out at the site during 20th–22nd June 1995, but with infiltration over a much smaller area and with more dilute tracer. In this experiment, 300 litres of tracer (conductivity approximately 1.5 S m^{-1}) were injected over a 1.5 m by 2.0 m grid in 50 hours, giving an average loading rate of 48 mm day^{-1}. Here, the tracer was not detected by electrical imaging except very near to the surface, so the experiment described above was devised, with both increased injection area and increased tracer conductivity compared with its forerunner. All subsequent references to 'the tracer experiment' refer to the larger injection experiment.

Results

QUANTIFICATION OF ERRORS

Hydrological interpretation of the images requires that the noise within the data sets is small. In this survey, the main source of noise was expected to be poor electrode contact with the powdered chalk grout. Inversion of noisy data can result in artificial resistivity structures in images which complicates hydrological interpretation. To minimise the effect of bad data on image structure any measurement with a reciprocal error greater than 3 % was removed prior to inversion. To estimate the magnitude of any residual resistivity structure caused by noise, an image was reconstructed using the variances of the reciprocal errors as the input measurements. This revealed that the maximum resistivity structure attributable to noise is insignificant compared to the resistivity structure observed.

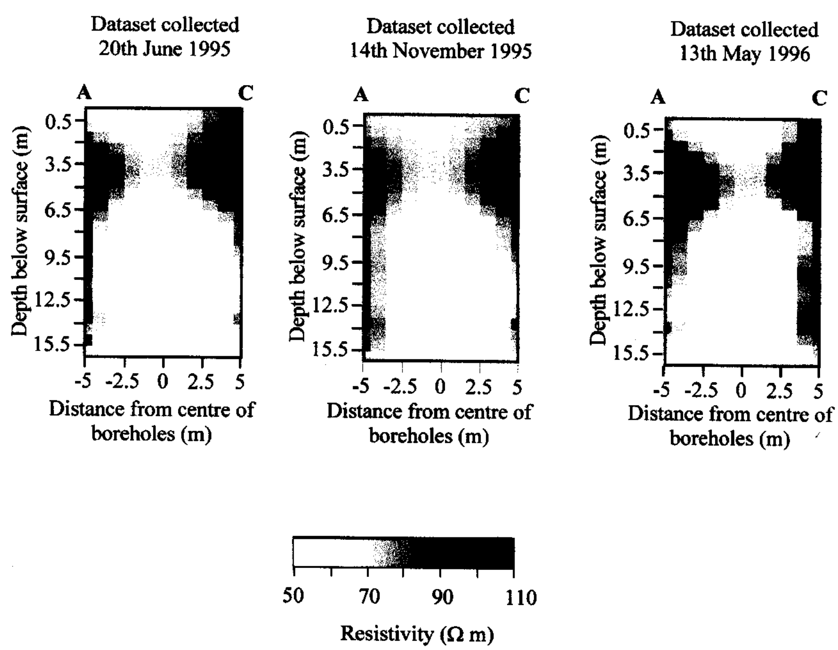

Fig. 5 *Resistivity structure from cross-borehole measurements made at three times prior to tracer injection.*

IMAGES PRIOR TO TRACER INFILTRATION.

Three cross-borehole derived resistivity distributions taken at three dates over eighteen months prior to the tracer experiment are shown in Fig. 5, where darker shading indicates higher resistivity. They reveal an electrically resistive (>110 m) layer between the surface and about 5 m depth. Between 5 m depth and the full depth imaged (15.5 m), the resistivity is lower (down to around 50 Ωm). The resistivity distributions for these three dates do not differ significantly from variations that could be attributed to measurement errors. Complications to seasonal comparison caused by the earlier tracer experiment, which took place shortly after the first image shown here was taken, are believed to be minimal due to the limited electrical response to this tracer. Also, allowing for the different investigation volume of the two techniques, there is good correspondence with downhole resistivity measurements obtained from the deep borehole at the site (Fig. 4) during February 1996 (Buckley and Talbot, 1996). Buckley and Talbot's measurements show a resistive layer (>200 Ωm) down to about 7 m depth underlain by a less resistive layer, with a resistivity minimum at about 12 m (50 Ωm), which indicates a prominent marl band. The results of surface electrical imaging performed at various sites on the interfluve suggest that the resistivity layering seen in the cross-borehole image of the tracer infiltration area is laterally continuous across the top of the interfluve.

TRACER INFILTRATION

Variations of resistivities from their initial values during and following the tracer injection are shown in Fig. 6 (darker shading represents decreased resistivity, white areas indicate no reduction). During tracer injection, there is (1) a marked decrease in resistivity in the top 3 m that can be distinguished after only 8 hours and is fully developed after 31 hours (2) little change in resistivity between

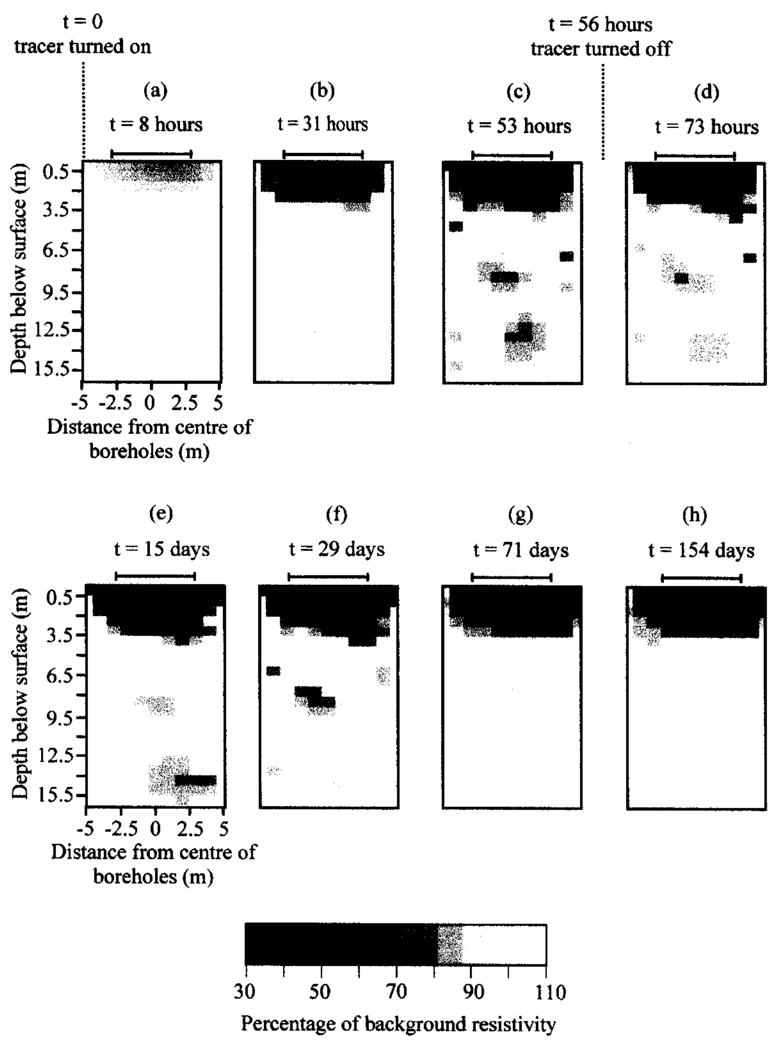

Fig. 6 *Images of resistivity change during and after tracer injection. Borehole A to left in all images. Horizontal bar shows infiltration area.*

3 and about 7 m and (3) a non-uniform decrease in resistivity in the lower half of the section, between about 7 m and 15 m depth, that can be seen after 31 hours and is fully developed after 53 hours. The resistivity pattern below 7 m was essentially unchanged over the first 29 days after injection ceased (see Fig. 6d–f). After 71 days, the resistivity at depth had recovered towards the background distribution and this recovery was confirmed by the data set collected after 154 days. Lateral migration of tracer was monitored by surface electrical imaging using the six arrays shown in Fig. 4. These surveys indicated that most of the tracer remained within the infiltration area.

Discussion

VALUE OF ELECTRICAL IMAGING IN MONITORING TRACER TESTS IN THE UNSATURATED ZONE.

The value of electrical imaging depends on the extent to which changes in resistivity are significant hydrologically. In this interpretation, it is assumed that the resistivity change is caused by a combination of a change in pore water salinity and a change in degree of saturation as tracer penetrates the chalk. In this case, each parameter (square in the images of resistivity change, Fig. 6) can be considered a 'sensor' of tracer migration representative of a 0.75 m deep by 1.0 m wide sample of the between-borehole medium. Darker colours in the images indicate areas where change is observed: following this interpretation of resistivity change, tracer transport is assumed to be occurring through these areas.

White regions of the images indicate either (1) sections not invaded by tracer, or (2) sections through which transport occurred via discrete pathways beyond the resolution of the imaging technique. Resolution is limited to the size of the 'sensor' (parameter). Hence, in this study, vertical tracer transport via discrete pathways less than 0.75 m wide may not be detected. The resolution of each 'sensor' could be improved by reducing the borehole spacing. However, this reduces the area of the medium investigated between boreholes.

The value of electrical imaging to the investigation of the hydraulics of the unsaturated zone is emphasised by the continuous spatial information obtained. Each image is made up from a total of 220 parameters ('sensors' of tracer migration). These 'sensors' are spatially continuous throughout the image plane. Such a sampling density would not be possible using standard hydrological instrumentation.

The value of electrical imaging is also demonstrated by the temporal information obtained. Each image reveals information on the tracer distribution at a certain time. The sequence of images over time reveals temporal changes in the distribution of tracer (Fig. 6) which may reveal the type of hydraulic processes activated by tracer loading. Assessment of tracer migration using repeated core sampling methods can disrupt natural transport mechanisms and confuse interpretation of hydraulic processes. In contrast, the medium investigated away from the boreholes is unaffected by the electrical imaging procedure. This results in a consistent and smooth variation between consecutive images (Fig. 6), which facilitates interpretation.

In field-scale studies of the unsaturated zone, interpretation of electrical imaging will normally only be qualitative. This is because the relationship between the resistivity change and tracer concentration cannot be determined. If (1) moisture content at each sensor remained constant with time, and (2) effective porosity, native pore water salinity and initial moisture content could be considered spatially constant, then the approximately linear relationship between solute electrical conductivity and solute concentration could be used to quantify the resistivity change for each sensor as a change in tracer concentration. It is clear that such conditions are unlikely to be met in field-scale studies of the unsaturated zone. In particular, variations in moisture content will certainly occur. This is the primary limitation of electrical imaging of tracer transport in the unsaturated zone.

Hydraulic implications of the results of electrical imaging at the study site

The sequential images of resistivity change (Fig. 6) are believed to give an indication of the hydraulic processes operating during tracer injection at this site. The large decrease in resistivity of the soil zone and upper 2 m of chalk (top 3 m or so) during tracer injection reflects rapid wetting caused by tracer infiltration. This decrease is persistent, which indicates that tracer entered the intergranular matrix of the weathered chalk blocks. These do not drain easily as the pore size is so small (d_{50} diameter = 0.4 μm, Price *et al.*, 1976).

As the resistivity was reduced significantly in several regions below 7 m depth (Fig. 6c–f), tracer transport to the lower half of the section must have occurred. This indicates the initiation of a hydraulically conductive preferential transport mechanism during tracer loading. Transport is unlikely to have occurred along or close to the boreholes containing the electrodes, as these appear as resistive features in the cross-borehole images (the chalk powder grout is relatively resistive).

This evidence for considerable tracer transport to depths greater than 7 m must be reconciled with the fact that the zone between 3 m and 7 m depth shows little change in resistivity. The suggested hydraulic interpretation is that preferential flow occurred between 3 m and 7 m depth via either a single natural fracture or a few, discrete, steeply inclined fractures of insufficient width to be resolved from electrical imaging. The plausibility of this interpretation was tested using resistivity modelling. A simple model of a 100 Ωm medium with a 20 Ωm region shaped to simulate the proposed tracer distribution is

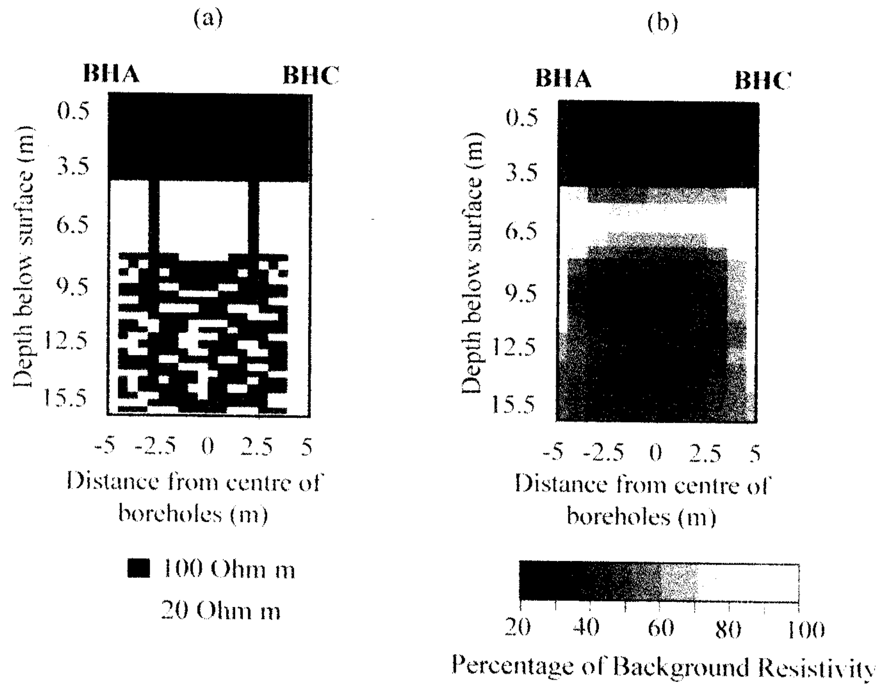

Fig. 7 *Results of synthetic ERT modelling: (a) synthetic tracer distribution includes two vertical fissures between 3.75 m and 7.00 m. (b) image of resistivity change caused by synthetic tracer shows that fissures are not resolved.*

shown in Fig. 7a. A synthetic data set was generated and contaminated with 3 % noise. Reconstruction of the resistivity change (relative to a homogeneous 100 Ωm medium) caused by this tracer distribution illustrates that the two discrete macrofissures between 3.75 m and 7.00 m are not resolved (Fig. 7b). The response to this tracer distribution is similar to that observed from the field measurements.

The resolution of the tracer below 7 m depth suggests that significant lateral spreading out of the fractures occurred at about 7 m. This lateral spreading may have been caused by interception of the tracer by marl layers. If this interpretation is correct, vertical heterogeneity in solute transport mechanisms has been identified at this site. As noted in the introduction, Ellsworth and Jury (1991) state that such vertical heterogeneity causes significant problems in the description of solute transport. These results suggest that electrical imaging may be an effective way of characterising the influence of heterogeneity. The hydraulic implications of the electrical imaging performed at this site are summarised in Fig. 8.

Calculated approximate transport rates support the operation of a fissure flow mechanism during tracer loading. Fig. 6b indicates that tracer had reached a depth of 15 m after only 31 hours of tracer injection. This places a lower bound on the seepage velocity of 11.6 m day^{-1}. This rate is probably an underestimate as (1) tracer could have reached these depths at some point in time between the 8 hour and 31 hour data sets, and (2) low concentrations of tracer, insufficient to show up on the images, could have reached the region even before 8 hours. As the maximum hydraulic conductivity of Kilham Chalk is only 0.3 mm d^{-1} (B. Clennell 1995, pers. comm.), these transport rates indicate fissure flow.

Fig. 6e–f shows that below 7 m recovery towards the background resistivity distribution had occurred after 71 days. This indicates reduction of tracer concentration within this zone, possibly due to flushing during periods of heavy rainfall that occurred in July. This flushing would be via the macrofissure network believed to have allowed rapid tracer transport to this depth. This recovery is not observed in the upper 3 m which is consistent with very slow drainage of intergranular pore fluid.

Conclusions

Cross-borehole electrical imaging of tracer transport in the unsaturated zone at a site on the UK Chalk aquifer has been performed. The value of electrical imaging of unsaturated zone hydraulic mechanisms is illustrated by the following factors: (1) each parameter of the electrical image can be considered a 'sensor' of saline tracer transport, (2) the high density of 'sensors' within the image provides excellent spatial information, (3) this information is spatially continuous throughout the image, and (4) sensing tracer transport is non-invasive, allowing repeated temporal sampling without disruption to operative hydraulic processes. In contrast, direct tracer sampling methods are limited by (1) a low density of sampling points necessitat-

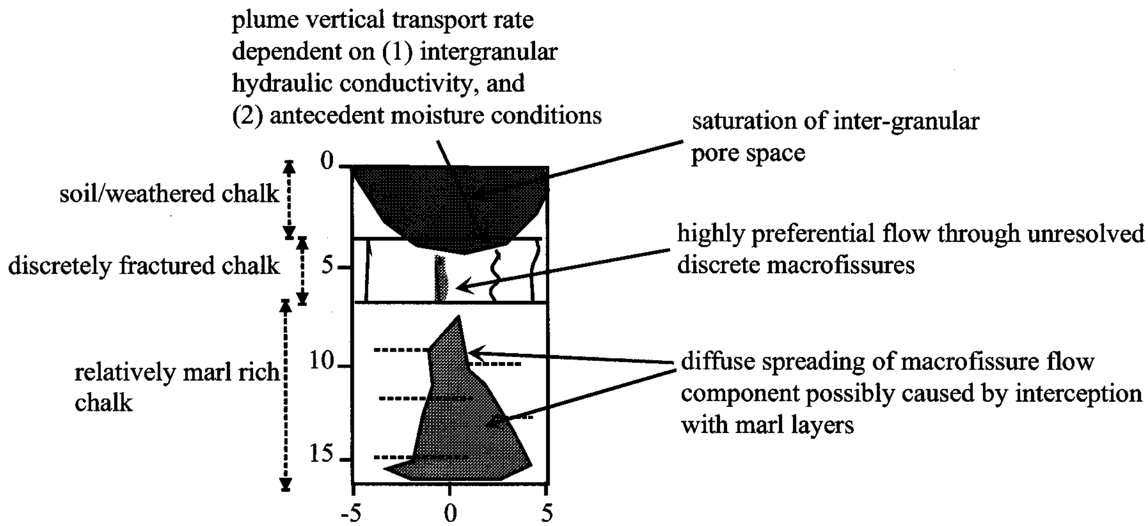

Fig. 8 *Summary hydraulic interpretation of observed resistivity change caused by tracer injection. Scale is in metres.*

ing interpolation between measurements, and (2) disruption of natural hydraulic processes caused by repeated temporal sampling.

The primary limitation of electrical imaging of tracer transport in the unsaturated zone is that hydrological interpretation is qualitative. This is because the electrical 'sensors' are only an indirect measure of tracer concentration. The electrical response caused by tracer transport in the unsaturated zone is due primarily to both a reduction in pore water resistivity and an increase in moisture content. The effects of these two factors cannot be separated. In contrast, direct sampling methods give a direct measure of tracer concentration. A second disadvantage of electrical imaging is that the resolution of each 'sensor' is limited (although resolution is improved by reducing the between-borehole spacing).

Electrical imaging during a tracer test is reported where saline solution was infiltrated over an 18 m^2 area of Chalk for 56 hours. Electrical imaging was performed prior to, during, and up to three months after tracer injection. The infiltration rate used was representative of an extreme (but feasible) rainfall event for the study area. Hence, the response to tracer injection observed in the electrical images may not be representative of normal hydraulic loading at this site. The hydraulic mechanisms inferred from the interpretation of temporal changes in the electrical images are (1) increased saturation of the soil and entry of tracer into the intergranular pore space in the top 2 m of chalk (2) fissure flow, possibly to the base of the section (15 m depth) in less than 2 days, which is not resolved in the electrical images, and (3) horizontal spreading of tracer (probably on a marl layer or layers) in the lower half of the section.

This tracer test demonstrated the value of electrical imaging of unsaturated zone hydraulic mechanisms. Assuming the hydrological interpretation of the electrical images to be correct, the images revealed the simultaneous operation of an intergranular and a fissure flow mechanism at the level of tracer loading applied in this study. Furthermore, the results suggest that electrical imaging can assist identification of vertical changes in transport mechanisms. Such visual information may help improve the description of solute transport at field sites.

Further investigation of the value of electrical imaging for the description of transport in the unsaturated zone is recommended. Ideally, the opportunity to correlate changes detected by the electrical 'sensors' with changes in hydrological properties observed from direct sampling methods is required. Funding constraints prohibited such an approach in this study. It is hoped that such an integrated approach will form the basis of future investigations of unsaturated zone transport using electrical imaging.

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