Ph.D. thesis
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Hydrogeophysical investigations of unsaturated flow and transport

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Preface

This thesis has been submitted as part of the requirements for the degree of Ph.D. at the Faculty of Science, University of Copenhagen, Denmark.

The work presented herein was carried out at the Section for Geology at the Department of Geosciences and Natural Resource Management from September 2009 to June 2014 under the academic supervision of Professor Karsten Høgh Jensen, Assistant Professor Majken C. Looms Zibar, and Professor Lars Nielsen. Professor Andrew Binley, University of Lancaster, UK, acted as external co-supervisor.

The thesis consists of the following published papers and paper manuscripts:


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Summary – English
The objective of the present Ph.D.-study is to further investigate unsaturated flow phenomena, which are generally considered complex and unpredictable. Hydrogeophysical methods are used for assessment of the flow and transport processes during four field experiments that were carried out at three different sites in Denmark. The sites at Hjelm Hede, Arrenæs and Voulund are all characterized by thick unsaturated zones that consist almost entirely of sand. The first experiment was a dye tracer infiltration at Hjelm Hede, which was monitored using high-resolution reflection Ground Penetrating Radar (GPR). Geophysical datasets obtained before and after infiltration were compared to dye staining patterns seen in an excavated profile. It was found that water had infiltrated in a highly irregular manner, and the GPR data showed that moisture content had increased well below the extent of the dye staining. Second, a point injection experiment was carried out at Arrenæs, in which a water tracer was added at 1.5 m depth for 5 days and subsequently monitored using three-dimensional cross-borehole Electrical Resistivity Tomography (ERT) and two- and three-dimensional GPR. A previous experiment at the site had revealed that the topsoil diverted water laterally, and therefore it was decided to inject water below the topsoil. The tracer plume as imaged by the geophysical data was compared to grain size analysis from the field site and it was found that small changes in grain size and sorting degree were responsible for initiating irregular development of the tracer plume, which expanded more laterally than vertically. Spatial moment analysis was applied and relevant moisture content threshold choices in delineating the tracer plume were discussed. The same threshold value was not found for the three types of data. Mass balance calculations revealed that two- and three-dimensional GPR show similar results and that tracer mass was severely underestimated by three-dimensional ERT. Another forced infiltration experiment was carried out at Arrenæs; this time water was added across a large area at a high rate for 14 days. Moisture content development was monitored using cross-borehole GPR and relative gravity measurements. GPR data were used as a means of ground-truthing the gravity data, which had not previously been used in similar experiments. For the first week of infiltration the mass balances match, but at that time the water front has reached the bottom of the GPR domain, which cannot account for the entire mass anymore. Likewise, an increase in gravity was no longer seen because the measurements are not sensitive to changes beneath this depth. GPR data revealed that flow in the measured domain was highly irregular. A three-dimensional hydrological model with hydraulic parameters and spatial correlation lengths similar to those found at the site was then developed. The moisture content development seen in the model during a synthetic infiltration was compared to actual GPR data to confirm that the same types of flow were present in the model. Next, a suite of similar models were set up, with different spatial correlation lengths but the same hydraulic parameterization. A particle tracking analysis was performed and the arrival time distribution of a suite of particles was compared to a homogeneous one-dimensional flow and transport model with added dispersion. For large spatial correlation lengths, it is concluded that the commonly applied assumption of one-dimensional flow in the unsaturated zone can be valid. In the last experiment reported here, we used cross-borehole ERT for estimation of natural recharge based on long-term monitoring of the movement of a saline tracer at the Voulund field site. ERT data were compared to samples obtained from core drillings from the site, and it was found that the position of the plume with time was well-resolved in the ERT data, although concentration values were smoothed in the inversion procedure and thus lower than those found in core data. The final value of recharge of 516 mm/year is in agreement with a recharge
estimate based on lysimeter drainage measurements from the same site. In order to calculate the natural recharge it was necessary to assume that unsaturated flow was vertical and homogeneous. Such an assumption can be difficult to justify, however the results from the three-dimensional modelling at Arrenæs show that it may be valid if the spatial correlation lengths found in the (sandy) subsurface are high.
Resume – Dansk

rapporteret her, anvendes borehuls-ERT til estimering af naturlig grundvandsdannelse. En salt-tracer blev infiltreret som en naturlig regnhændelse på Voulund og tracerfrontens bevægelse blev herefter monitoreret med ERT data over næsten et år. Tracer-koncentrationer estimeret fra de geofysiske data blev sammenlignet med prøver fra kerneboringer, og det konkluderes, at der var god overensstemmelse mellem de to typer målinger. Dog var de maksimale koncentrationsværdier lavere i ERT data, på grund af udglatningseffekter i inversionsproceduren. Grundvandsdannelsen estimeres til 516 mm/år, hvilket er i fin overensstemmelse med et tilsvarende skøn baseret på dræningsdata fra lysimetre på samme feltområde. For at beregne den naturlige infiltration var det nødvendigt at antage, at umættet vandbevægelse på Voulund er lodret og homogen. Resultaterne af den tredimensionelle modellering af Arrenæsdata viser, at en sådan antagelse godt kan være gyldig, forudsat at de rumlige korrelationslængder på Voulund er høje.
Abstract
Experiments were carried out at three different field sites in Denmark, which all are characterized by thick unsaturated zones that consist almost entirely of sand. The first experiment was a dye tracer infiltration, which was monitored using high-resolution reflection Ground Penetrating Radar (GPR). Geophysical datasets were obtained prior to and after infiltration and compared to dye staining patterns seen in an excavated profile. It was found that the water had infiltrated in a highly irregular manner, and the GPR data showed that moisture content had increased well below the extent of the dye staining. Second, a point injection experiment was carried out in which a water tracer was added at 1.5 m depth for 5 days and subsequently monitored using three-dimensional cross-borehole Electrical Resistivity Tomography (ERT) and two- and three-dimensional cross-borehole GPR. Results were compared to grain size analysis from the field site and it was found that small changes in grain size and sorting degree were responsible for initiating irregular development of the tracer plume. Spatial moment analysis was applied and relevant threshold choices in delineating the tracer plume were discussed. Mass balance calculations revealed that two- and three-dimensional GPR show similar results and that tracer mass was severely underestimated by three-dimensional ERT. At the same site (but 30 m away) another forced infiltration experiment was carried out, in which water was added across a large area at a high rate for 14 days. Moisture content development was monitored using cross-borehole GPR and relative gravity measurements. Both types of data show similar mass balances for the first week of infiltration. GPR data reveal that flow in the measured domain was highly irregular. A three-dimensional hydrological model with hydraulic parameters and spatial correlation lengths similar to those found at the site was then developed. The moisture content development seen in the model during a synthetic infiltration was compared to actual GPR data to assure that the same types of flow were present in the model. Next, a suite of similar models were set up, with different spatial correlation lengths but the same hydraulic parameterization. It was then concluded that for large spatial correlation lengths the commonly applied assumption of one-dimensional flow in the unsaturated zone can be justified. Finally, cross-borehole ERT is used for estimation of natural recharge based on long-term monitoring of the movement of a saline tracer. ERT data is compared to samples obtained from core drilling at the same site, and it is found that the position of the plume with time is well-resolved in the ERT data. The final recharge value of 516 mm/year is compared to that calculated from lysimeter drainage at the same site, and the two numbers are in agreement.
**Objectives**
The objectives of the present Ph.D.-study are to investigate unsaturated zone flow and transport processes using hydrogeophysical methods through experiments carried out at three different field sites in Denmark. Other studies have been carried out at each field site, and the experiments and results presented in this thesis builds on and expand the previous findings. Common for the three field sites is that the unsaturated zone is in general considered relatively uniform because the subsurface below the topsoil consists mainly of sandy alluvial sediments. Therefore it is also possible, at least to some extent, to compare results obtained at the different field sites.

**Introduction**
In Denmark, 99% of water for consumption comes from untreated groundwater, and as such much effort is put into protecting this valuable and unique resource, which is under pressure from both climate change as well as contamination threats from industry and in particular agriculture. The EU Water Framework Directive (WFD) states that all surface water bodies should be clean by 2015. This implies that protecting and cleaning groundwater resources should also be prioritized, as these ultimately feed the surface water systems. The WFD also requires that necessary action is taken on the catchment scale, regardless of administrative or political boundaries, since this is the natural hydrological and geographical unit (European Commission, 2014). Protecting water resources is thus a priority on both national and international levels. There are many limitations to our knowledge about the in- and outgoing water fluxes of catchments, which results in difficulty closing the water budget on this scale (Henriksen and Sonnenborg, 2003; Stisen et al., 2012). The HOBE hydrological observatory (www.hobe.dk) was established in 2007 after receiving grants from the Villum Foundation, and it is based in the Skjern River Catchment in western Jylland, Denmark (Figure 1). The research activities within the HOBE project aim at reducing water balance uncertainty at catchment scale by improving our knowledge of the fluxes of the hydrological cycle at different spatial and temporal scales (Jensen and Illangasekare, 2011). The geological setting in the Skjern River Catchment is representative of most of western Denmark and the results obtained in the HOBE project can therefore be extended to a larger region and other catchments.

The availability of water in the unsaturated zone facilitates vegetation growth, and the flow of water out of the unsaturated zone regulates groundwater recharge, which ultimately determines how much water is available for consumption, industrial purposes and irrigation (Dingman, 2002). Moreover, it is in the unsaturated zone that contaminants are retarded or degraded by physical, chemical or biological processes. Needless to say, the whereabouts and condition of water in this zone has significance on many levels. Although situated right beneath our feet the unsaturated zone is difficult to access because obtaining measurements typically requires the use of invasive techniques.

The field of hydrogeophysics combines hydrology and geophysics insofar that geophysical methods are used to measure hydrological variables, such as soil moisture content and solute concentration, and identify hydraulic parameters (Rubin and Hubbard, 2005). Traditionally these variables and parameters are estimated using e.g. point measurements and laboratory experiments on small samples that do not necessarily account for the spatial variation found at the field scale. Moreover, for hydrologic modelling purposes the needed scale is usually even larger, and confidence in the input
parameters for such models is crucial for the reliability of the model results. Hydrogeophysics can help bridge the gap between point measurements and the much larger scale information needed for e.g. management decisions. In this thesis work, three hydrogeophysical methods were applied for investigations of moisture content and/or tracer concentrations in the unsaturated zone; Ground Penetrating Radar (GPR), Electrical Resistivity Tomography (ERT) and hydrogravimetry. Although more hydrogeophysical methods exist, GPR and ERT are by far the most widely used (Binley et al., 2010).

In ground penetrating radar (GPR), an electromagnetic (EM) wave is emitted from a transmitter antenna and recorded at a receiver antenna. GPR can be deployed as either reflection or transillumination surveys (Annan, 2005). In a reflection survey the transmitter and receiver are both at the surface and the transmitted signal is reflected at interfaces in the subsurface with different dielectric properties. Reflection GPR surveys are therefore suitable for geologic mapping, since geologic boundaries cause reflections The method can also be used for groundwater level mapping, as the EM signal will be reflected there. Reflection GPR is completely nondestructive, since measurements are obtained from the surface; however, the penetration depth is limited in areas containing conductive material because of signal attenuation. Thus, the method is highly applicable in areas containing dry sand, like the field sites presented in this thesis.

For transillumination surveys GPR measurements are made between boreholes and it is the direct electromagnetic wave, between the transmitter and receiver, which is recorded (Annan, 2005). By comparing the received signal to a calibration signal (obtained in air) the average velocity of the EM wave through the subsurface can be calculated for estimation of moisture content, whereas the shape of the waveform can be used for estimation of soil conductivity. In the borehole configuration, the GPR method is somewhat invasive, because it requires access boreholes for deployment of antennas; however the borehole method does not suffer from loss of resolution with depth, and can even be used in areas where, for example, the topsoil consists of conductive material.

Two main methods of acquiring cross-borehole GPR data are usually adopted; the Zero Offset Profiling (ZOP) and the Multiple Offset Gather (MOG) (Annan, 2005). For ZOP measurements the antennae are lowered simultaneously into two boreholes and the direct (horizontal) EM wave between them is recorded for the entire depth of the borehole. Determining the EM velocity for all GPR traces with depth provides a 1D profile of the average EM velocity in the subsurface between the boreholes. In the MOG data acquisition, one antenna is fixed at a certain depth, while the other is moved downward at pre-defined intervals. This process is then repeated with the fixed antenna at another depth, and finally the process is reversed so the moving antenna becomes the fixed antenna and vice versa. In this manner the subsurface between the two boreholes is covered by many (crossing) EM waves, and inversion of the arrival times can produce a tomographic image of the two-dimensional distribution of velocity between the boreholes.

In the Electrical Resistivity Tomography (ERT) method it is the electrical properties of the subsurface that are measured. This method can also be deployed from the surface but suffers from the same loss of resolution with depth as surface reflection GPR. In the borehole setup electrodes are installed along tubes inserted in boreholes, and measurements are obtained by applying a measurement scheme consisting of multiple combinations of current and potential electrodes (Binley and Kemna, 2005). Current is injected between the two current electrodes and the potential difference between
the other two electrodes is measured. Thousands of measurements can be obtained within hours using modern standard equipment with multiple recording channels. ERT data can be obtained between two or more boreholes, depending on whether a two-dimensional or three-dimensional image of the resistivity distribution is sought.

Using either reflection or transillumination GPR it is possible to acquire repeated measurements using the same configurations and geometry, and for ERT it is straightforward to record multiple data sets consisting of the same series of measurements. This makes both these hydrogeophysical methods highly suitable for time-lapse studies (Huisman, 2003; Binley and Kemna, 2005).

In order to produce tomographic two-dimensional or three-dimensional images of the distribution of resistivity or EM wave velocity in the subsurface it is necessary to invert the collected hydrogeophysical data. This is most often done using an Occam’s type inversion which seeks to find a solution to the inverse problem that has a good misfit between measured and predicted observations while at the same time honoring some pre-defined smoothness criteria (Constable, 1987; LaBrecque and Yang, 2001; Day-Lewis et al., 2005). Smoothness criteria are added to prevent the model solution from being too complex. Constraints can also be added to the problem based on empirical knowledge of for example geological structures of the subsurface or as penalties for deviations from the background model.

Gravity measurements can either be obtained as absolute or relative data. In the latter case the recorded signal is compared to a reference station, where the conditions are assumed known or constant. Likewise, all measurements must be corrected for drift, while (natural or anthropogenic) seismic activity can effectively ruin measurements by introducing high amounts of noise. Time-lapse gravity data provides a direct measurement of the change of e.g. water mass in the soil, and thus the data can be used in calibration of hydrological models (Christiansen et al., 2011).

Measurements of physical properties obtained from GPR and ERT data are related to hydrological parameters or variables through petrophysical models, such as the empirically derived Topp or Archie relationships (Topp et al., 1980; Archie, 1942). In the case of using gravimetry to infer e.g. moisture content, there is no need to apply a petrophysical model, since the gravity response is an actual measure of the change in e.g. water amount in the subsurface.

The Topp relationship relates the dielectric permittivity and the volumetric moisture content of a soil (Topp et al., 1980). Since water is the most dielectric material found, the dielectric permittivity of any soil is highly dependent on its moisture content. Modified versions of the Topp relationship have been developed over the years; in this thesis we will for instance also make use of the model of Ferre et al. (1996) which is a linear approximation to the Topp relationship.

Archie (1942) developed a model relating the resistivity of a geologic formation to the content and character of the in situ fluid. The original use of this relationship was in the oil and gas industry, in which positive resistivity anomalies can be indicative of the presence of hydrocarbons instead of water in the pore space. Today, however, Archie’s law is used extensively for hydrological purposes, because the moisture content and/or solute electrical conductivity can be determined (Lesmes and Friedman, 2005). As such, resistivity measurements can be used for both investigating the
whereabouts of water in the soil/subsurface as well as e.g. contamination assessment, provided the pollutant is conductive or resistive.

**Field sites, previous studies and paper summaries**

This Ph.D thesis covers work carried out at three different field sites located in Denmark: Hjelm Hede, Arrenæs and Voulund (Figure 1). Hjelm Hede is a heath area situated in northern Jylland, Arrenæs is a small headland into the Arresø lake in the northern part of Sjælland, and the Voulund field site is situated on a farming field in the Skjern River Catchment in western Jylland. Common for all three field sites is that the subsurface consists almost entirely of sand, and that the unsaturated zone is thick (>5 m). Further, the sandy subsurface makes them suitable for geophysical investigations using Ground Penetrating Radar (GPR). The field sites at Hjelm Hede and Voulund are both situated on glacial outwash plains and as such the processes of unsaturated flow are assumed to be comparable for those sites, while at the same time representing the main geological setting in western Denmark. The subsurface at Arrenæs has a different geological history and the material is younger, but the conditions are also comparable to Hjelm Hede and Voulund because of the glacial origin. In the following paragraphs each field site will be presented in further details. The motivation for the experiments carried out in the present Ph.D.-study will be highlighted and the papers/manuscripts relating to each experiment are summarized.

![Figure 1](image)

*Figure 1*
Location of field sites. Blue area outlines the Skjern River Catchment
**Hjelm Hede**

Hjelm Hede is a 12 km² heath area in Northern Jylland that has formed over the last millennia as a result of the deforestation that took place as more and more land was needed for farming and grazing. The soil is a podzol and the subsurface mainly consists of medium to coarse sand, which was deposited as glaciofluvial sediments during the termination of the last glaciation (Ladekarl et al., 2005). Vegetation at the site is low, up to 60 cm, and consists of heather and small shrubs (Ladekarl et al., 2005). Today the area is a conservation site and is maintained by e.g. burning and grazing to prevent forest growth, which would otherwise happen. The groundwater level is found approximately 21 m below the surface. The chosen field site is located at 56.488954 lat., 8.904092 long. in the southern part of the heath area.

**Dye tracer experiment, April 2008**

From 1996-2000 water content to a depth of 6 m was measured using TDR-probes inserted every 50 cm with duplicate probes at 2.5 and 6 m depth for comparison (Ladekarl et al., 2005). The measurements show that nonuniform natural infiltration takes place at the site and it was decided to carry out a tracer experiment at the site in order to assess the infiltration patterns. Figure 2 shows pictures from the experiment and results are presented in Paper 1, “Visualizing unsaturated flow phenomena using high-resolution reflection ground penetrating radar” (Haarder et al., 2011).

In the field experiment 100 mm of Brilliant Blue dyed water was infiltrated across a 3-by-3 m area. The purpose of the experiment was to investigate the applicability of high-resolution reflection ground penetrating radar for nondestructive visualization of unsaturated flow patterns at a site where non-uniform infiltration had previously been observed. Surface reflection GPR data sets were obtained prior to and the day after infiltration for a 5-by-5 m area covering the entire infiltration area. It was made sure that the GPR datasets were comparable, i.e. the 100 data lines were obtained in the same configuration before and after tracer application. The area was then excavated to a depth of 2.2 m and the flow patterns highlighted by Brilliant Blue were investigated.
Dye staining was more or less uniform to a depth of 1 m after which infiltration fingers form and continue quite deep in to the subsurface (>2 m). A redoximorphic horizon containing precipitated Fe-oxides was encountered at 1.5 m depth and seemed to cause further development of heterogeneous flow. Likewise, cemented root remnants were also responsible for diversion of flow, and we found clear evidence of capillary barriers, where water had moved around small bodies of coarse sand.

GPR data from before and after tracer application were compared in terms of reflection arrival time and amplitude level. With this approach it was possible in the GPR data to assess the induced changes in moisture content, which cause both reflection delay and loss of signal energy. Results showed that the primary reflection delay and amplitude change were found within the tracer application area, albeit at much deeper depths than the dye staining patterns suggested. Although it was not possible to resolve detailed water flow patterns using the GPR data the results highlight the potential of GPR to nondestructively map unsaturated flow phenomena in some detail.

**Arrenæs**

The field site at Arrenæs is situated 25 m above the Arresø lake level and the 20-25 m thick unsaturated zone consists almost entirely of glaciofluvial sand deposited during the last glaciation. The very shallow subsurface has been observed to consist of moraine clay in nearby wells. In 1995 a test site for artificial infiltration was established, in which lake water is pumped up and infiltrated in
large basins or via sprinklers with the aim of filtering the polluted lake water so it becomes suitable for consumption. The test site was shut down in 2012 and has since been converted to a recreational area. Arrenæs was chosen for the artificial infiltration experiment since the thick and highly permeable vadose zone allows for fast infiltration to the groundwater and thus a high production of artificial groundwater.

Figure 3
Schematic of field sites A, B, and C at Arrenæs and picture from the field site (photo: L. Christiansen)
Note that GPR access tubes have been installed after each core was obtained

Outside the artificial recharge area a cross-borehole hydrogeophysical array was established in 2004 consisting of 16 boreholes equipped with electrodes every 50 cm for electrical resistivity measurements and access tubes for GPR antennas (Looms, 2007). Each borehole array (site A and B, Figure 3) consisted of 4 ERT and 4 GPR boreholes, which were placed in the corners of 2 squares with diagonal lengths of 7 and 5 m, respectively. In 2009 the field site was expanded with the addition of
Site C (Figure 3), which is a borehole array consisting of 4 access tubes for GPR antennas placed in a square with 5 m in the diagonal. The boreholes extend through almost half of the unsaturated zone; at site A and B they extend to a depth of approximately 12 m, while the borehole depth at site C is approximately 11 m. In the present thesis, only data collected from site B and site C will be presented.

Core data was acquired from site B in 2008, when 4 cores were obtained using the Geoprobe direct push rig equipped with a MacroCore soil sampling system (Geoprobe Systems, KS, USA) (Bakmand-Mikalski and Karlsson, 2008). The 4 cores were placed on the sides of the square forming the GPR array for site B. Additionally, five cores from site C were obtained in 2010, also using the Geoprobe equipment. Four of the cores were placed along the sides of the GPR array square, while the fifth core was obtained from the middle of the array. Placement of cores in the different borehole sites can be seen in Figure 3.

**Point infiltration experiment, October 2008**

Installations at Arrenæs were established as part of the PhD-work of Majken C. Looms, who carried out several tracer experiments, which were monitored using GPR and ERT measurements (Looms, 2007). The main experiment was a forced infiltration across site B, in which clean water was added at a constant and high rate for 20 days. After 4 days a saline tracer was added during 150 minutes (Looms et al., 2008). Looms et al. (2008) present the results of one- and two-dimensional moment analyses, in which flow and transport parameters were estimated. They found that 50% of the water and tracer mass was lost in the top of the subsurface, probably because of lateral flow close to (or on) the surface due to the presence of low-permeable layers containing clay and silt. The experiment was originally designed to avoid the resolution issues that arise from point injections and trench infiltrations (Binley et al., 2001; 2002a; Singha and Gorelick, 2005, Deiana et al., 2008). However, the loss of mass spawned the idea of carrying out a second experiment at the site, in which a water tracer was injected below the topsoil in order to avoid loss of mass. Figure 4 shows a few images from data acquisition in October 2008.

The results of the point injection experiment are presented here as Paper 2: “Comparing plume characteristics inferred from cross-borehole geophysical data” (Haarder et al., 2012). In this paper we explore the differences between hydrogeophysical approaches for imaging tracer migration from a point injection of water in the unsaturated zone at Arrenæs. Because earlier tracer experiments from the site suffered from massive loss of mass in the top 1 m of the subsurface we injected a water tracer into the sandy sediments at 1.5 m depth. The migration and development of the tracer plume was monitored during the 5 days of injection and for 5 days after injection had ceased.
The geophysical data that was acquired were two-dimensional and quasi-three-dimensional ground penetrating radar (GPR) and three-dimensional electrical resistivity measurements. The quasi-three-dimensional GPR data set was not originally acquired with the purpose of performing a three-dimensional inversion, but was collected as a densely sampled one-dimensional dataset. The results from the three methods showed similar characteristics of the tracer plume as it migrated through the unsaturated zone. We found that the lateral development of the plume was strong and that vertical movement of the center of mass was surprisingly slow. Both GPR data sets showed that a secondary plume formed at depth, whereas this was not captured by three-dimensional ERT because of resolution limitations.

Spatial moment analysis was applied to the different data sets for quantitative comparison of results and it was found that the choice of threshold value for delineating the tracer plume was extremely important, particularly for mass recovery. Three-dimensional ERT results severely underestimated tracer mass for all chosen thresholds due to resolution and sensitivity issues, whereas two-dimensional and three-dimensional GPR results overestimate tracer mass for low thresholds.
We compared our results to grain size measurements from a core obtained from the site to assess the cause of the lateral diversion of the injected water. Below the upper 0.5 m the subsurface consisted of sand with only minor contents of silt. However, the depth at which the lateral diversion of the tracer plume was initiated coincides with the presence of a few thin layers of coarser material than the dominating fine-medium sand. Although the three-dimensional extent of these coarse layers across the area was unknown, it is likely that they acted as capillary barriers and caused lateral diversion of flow on top of and around them. The level of impact these layers of <0.2 m thickness had on the movement of the tracer in this experiment was surprising and illustrates that a subsurface consisting of 100% sand does not necessarily give rise to homogeneous flow patterns, although this is often assumed.

The emergence of flow diversion and heterogeneous plume development due to small changes in lithology could be used as an argument for choosing lower threshold values, since a much larger part of the subsurface was probably affected by the tracer water, yet only with small increases in moisture content as a result. By choosing threshold values that assume that the plume development is homogeneous and uniform this effect is largely neglected.

**Area infiltration experiment, September 2009.**

The field experiment carried out at Site C in September 2009 was an area infiltration similar to that reported in Looms et al. (2008). However, the “new” borehole array was placed in an area where surface reflection GPR surveys revealed only little or no clay/silt in the topsoil. Therefore it was expected that the infiltrated water would not be diverted in the upper layers and that e.g. spatial moment analysis calculations would be able to resolve most of the mass. A few images from the field experiment are shown in Figure 5.

Cross-borehole GPR measurements were obtained almost every day during infiltration, which lasted 14 days. Measurements of relative changes in gravity were also obtained, and the data were used in a first attempt to calibrate a vadose zone model with time-lapse gravimetry data. GPR measurements were used as a means of ground-truthing and validating the gravity results, and the results are presented in Paper 3: “*Calibrating vadose zone models with time-lapse gravity data*” (Christiansen et al., 2011).

The data set obtained during the infiltration in 2009 was subsequently used in a more generic analysis of the validity of the assumption of one-dimensionality in unsaturated zone flow. The collected GPR data from the infiltration experiment at site C were inspected and analyzed in detail regarding the different types of flow patterns that occur. Based on geostatistical estimates of the spatial correlation lengths from Looms et al. (2010) and hydraulic parameterization from pedotransfer functions provided by Børgesen et al. (2005) a three-dimensional model of the field site was set up. Results of a synthetic tracer experiment were compared to the collected geophysical data in terms of moisture content development and water flow types. Additionally, a suite of three-dimensional hydrological models with the same overall parameterization but different spatial correlation lengths was developed with the purpose of assessing how the validity of assuming one-dimensionality varied with spatial correlation structures. Results of the analysis are presented in Paper 4, “*Dimensionality of unsaturated flow processes in sandy alluvial sediments*”.

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In Paper 3 time-lapse gravity measurements are used to infer hydrologic information about the unsaturated zone at Arrenæs, Denmark. Gravity measurements have the advantage of providing direct information about the change in water mass in the soil and are therefore not dependent on petrophysical relationships like other geophysical methods. A forced infiltration event across a 107 m² area for 14 days gave rise to a measurable gravity signal caused by the changes in moisture content in the subsurface.

Borehole GPR data sets consisting of both one-dimensional and two-dimensional measurements were obtained (almost) every day during infiltration (and for a week after). Moisture content changes inferred from the GPR data were compared to the applied irrigation rate to assess the water balance of the experiment, and it was found that after 7 days there was no longer an increase in mass even though water was still added at the surface. The reason for the loss of water was that the water front had reached the depth of the lower extent of the GPR boreholes (~11 m) and thus changes in moisture content beyond this depth were not captured by GPR. A similar development was seen for the gravity measurements, in which the gravity signal increases steadily during the first 8 days after which it stagnates before finally decreasing after irrigation ceased. This development implies that the gravity measurements are most sensitive to water mass changes in the upper ~10 m of the subsurface.

The gravity data was used in a hydrogeophysical inversion in which the gravity response was calculated directly based on the moisture content distribution given by the hydrological model. As a priori estimates of the van Genuchten hydraulic parameters laboratory measurements from borehole samples at the field site (although >30 m away) were used. The van Genuchten parameters were fitted either alone or in pairs, and it is concluded that a model with calibrated values of θ_s and n was the most reliable because it was also able to fit the observed data at late times.

As a first attempt to calibrate hydraulic parameters using time-lapse gravity data, this study highlights the applicability of gravimetric measurements for investigations in the unsaturated zone, albeit the lack of resolution with depth poses some limitations on its use. Combining gravity measurements with other, more well-established methods such as ERT and GPR, in a joint inversion set-up is recommended.
Although unsaturated water flow is often assumed homogeneous for practical purposes, many studies have shown that this is usually not the case. In Paper 4 the validity of assuming one-dimensionality in unsaturated zone flow modeling was explored based on the data collected in the infiltration experiment described above. Detailed analysis of the GPR ZOP data indicated that a variety of different types of flow were probably taking place although the subsurface consists entirely of sand and is considered homogeneous. We found indications of, for example, the classical piston flow water front movement as well as flow diversion induced by grain size differences, and fast vertical percolation through coarse material with only very little increase in moisture content.

It was then evaluated whether it was possible to represent the water flow patterns found in GPR data from the field experiment by modelling the infiltration experiment in three dimensions. For that
Summary – Hydrogeophysical investigations of unsaturated flow and transport

purpose, several models with hydraulic parameterization and spatial correlation structures similar to those found at the field site were set up and the model response to the infiltration was analyzed. We found that it was possible to recover most of the behavior seen in field data in terms of water flow patterns as well as moisture content values and water front movement.

Finally, a suite of three-dimensional models with the same hydraulic parameterization but different spatial correlation lengths were developed. A particle tracking analysis for natural and stressed conditions representing the infiltration experiment was performed. The results in terms of travel times and variation in travel times were then compared to a one-dimensional model with added dispersion. The results show, among other things, that for small horizontal correlation lengths (i.e. below approximately 5 m) the assumption of one-dimensionality even for subsurfaces consisting only of sand is probably not valid. In the case of large horizontal correlation lengths it seems justified to assume that flow is one-dimensional and vertical, and the results indicate that the dispersivity value needed in such a case should be less than the rule-of-thumb value of 1/10 of the transport length.

**Voulund (HOBE agricultural field site)**

The HOBE hydrological observatory ([www.hobe.dk](http://www.hobe.dk)) was established in 2007 in the Skjern River Catchment, which has an area of 2500 km$^2$ and is situated in western Denmark (Figure 1). The landscape was formed by glacial processes and the dominating landscape elements in the catchment are outwash plains and moraine sediments from the two previous glaciations, the Saalian and the Weichselian (Houmark-Nielsen and Kjær, 2003). The main land-use in the catchment is agriculture which makes up 85% of the total area (Jensen and Illangasekare, 2011).

The overall aim of the research activities within the HOBE research project is to improve the understanding of hydrological processes at the catchment scale since this is the appropriate scale for water management and legislation. One of the most fundamental issues in the hydrological sciences is closing the water balance, i.e. measuring and predicting the in- and outgoing fluxes in the hydrological cycle (Jensen and Illangasekare, 2011). Within the Skjern River Catchment several HOBE field sites were established in order to provide measurements of the hydrological fluxes on different spatial and temporal scales in areas representing the main land uses.

The most elaborate of the HOBE field sites is located in an agricultural field near Voulund in the eastern part of the catchment (See Figure 1). The site is equipped with numerous installations above and below ground for measurement of e.g. climate variables, isotopes, soil moisture, etc. In addition, four lysimeters with a total area of ~50 m$^2$ were installed in the cultivated field outside the fenced area (Figure 6).

A geophysical borehole array was installed in 2009-2010 consisting of 4 boreholes for GPR data acquisition and 5 boreholes equipped with electrodes for ERT data acquisition (Figure 6). ERT boreholes are placed in the corners and middle of a 5 by 5 m square and within this the GPR boreholes are placed in the corners of a 3.5 by 3.5 m square.
Summary – Hydrogeophysical investigations of unsaturated flow and transport

Saline tracer infiltration, September 2011

A saline tracer was added across a 142 m² area (encompassing the borehole array) as a natural precipitation event of 3.3 mm. During the following year the movement of the tracer front was monitored by ERT measurements on a daily to weekly basis with resistivity data obtained between 5 boreholes and 12 surface electrodes in order to estimate recharge at the site. GPR measurements were also obtained during the same period, but the data have not yet been analyzed in detail. During the same period 5 drill cores through the unsaturated zone to 6 m depth were obtained from within the tracer application area. The first core was obtained just prior to tracer application, and the following 4 were obtained with 2-month intervals, the last being drilled in April 2012. Soil water was extracted from each core for measurement of moisture content and solute electrical conductivity (EC). Results of the experiment are described in Paper 5, “Estimation of recharge using ERT data from long-term monitoring of saline tracer”, in which the findings are also compared with drainage data from the lysimeters at Voulund (Vasquez et al., 2014). Figure 7 shows images from tracer application and (GPR) data acquisition from Voulund.

ERT data was inverted using a difference inversion approach to produce three-dimensional tomographic distributions of resistivity in the subsurface. During the monitoring period, temperatures varied up to 15°C in the subsurface, and due to the positive correlation between temperature and
conductivity, temperature effects could not be neglected. All resistivity data were therefore normalized to a standard temperature of 7.5°C.

For simplicity in the further calculations we assumed that the subsurface could be represented by a one-dimensional model in which the resistivity mainly changes in the vertical direction. Median resistivity values for each depth were determined and solute EC was calculated using the Archie relationship (Archie, 1942). Tracer concentration in g/L was calculated using the Sen & Goode (1992) model for both ERT data and for core sample measurements and the two types of data were compared. In general, the core data showed higher tracer concentration peaks than the ERT data, although the two data types agreed on the position of the tracer with depth. The reason for the higher tracer concentration values in cores is probably that these can be considered point measurements.

Spatial moment analysis was applied to the ERT data set and the zeroth and first moment was calculated, i.e. the total tracer mass and position of the center of mass, respectively. Tracer mass was underestimated for the entire duration of the experiment with the highest mass recovery of 90%
found in January 2012. Other studies using ERT to estimate tracer mass have shown similar problems in reaching the full mass recovery particularly when the tracer peak is high and narrow (usually at early times) because of smoothing effects in the inversion (Binley et al., 2002; Singha & Gorelick, 2005, Doetsch et al., 2010). After January 2012 the tracer front reached 5 m depth and the entire saline tracer was no longer contained within the measurement volume.

Although the total tracer mass is underestimated we calculated the position of the center of mass using spatial moment analysis. The position of the tracer center of mass was well resolved until the end of April 2012. After this time more than 50% of the tracer mass had exited the measured volume, and it was no longer possible to calculate the center of mass. Recharge was estimated based on the center of mass movement over time and was estimated at a total value of 516 mm from September 2011 to May 2012. This value for recharge was considered to be only slightly less than the total recharge during the hydrological year 2011-2012 since the measurements covered the part of the year, in which recharge primarily takes place (August-May). Further, the value for recharge was comparable to that found using drainage data from lysimeters placed in the field only meters away from the ERT array (see Figure 6) (Vasquez et al., 2014).

Using the second spatial moment we estimated a dispersivity value of 0.25 m for the Voulund field site for an ERT data set where the center of mass is at 2.7 m depth. The calculated value was a little less than the empirical rule-of-thumb value for dispersivity, which is 1/10 of the transport length.

**Discussion**

Previously, the variability and dynamics of unsaturated flow has often been assessed by dye staining experiments, which is a powerful technique, where flow patterns in the soil are highlighted by the dye (Flury et al., 1994; Flury and Wai, 2003; Weiler and Flühler, 2004). Most dyes, however, are subject to retardation because they adsorb to the soil particles and therefore they can only be used for visualizing flow pathways, i.e. where the water has been, and not necessarily where it is. Further, to reveal the dye staining patterns it is necessary to excavate the subsurface, which is labor-intensive, expensive and irreversible under laboratory and field conditions. Nevertheless, dye staining experiments have revealed that preferential flow and fingering etc. exist and are common across a wide range of soil types (Flury et al., 1994, Wildenschild et al., 1994). Kung (1990) investigated flow paths in sand highlighted by dye staining and found that dipping layers and interfaces between sand of different grain sizes could initiate preferential flow. The presence of the redoximorphic horizon found at Hjelm Hede and its initiation of irregular flow is comparable to the concept of “fingered flow” described by Kung (1990). This type of irregular flow occurs when a uniform infiltration front splits into fingers after encountering a horizontal horizon, in which a fine soil overlies a coarser and dry sand layer (Kung, 1990). At Hjelm Hede, however, there was no change in grain size across the redoximorphic horizon but instead a small change in cementation, which had the same effect (Paper 1).

Because of the inherent drawbacks of dye staining, alternative methods for investigating complicated flow patterns in the unsaturated zone have been adopted. The experiment carried out in Hjelm Hede was an attempt to compare high-resolution information about moisture content with depth obtained
from reflection GPR to dye staining patterns revealed by excavation (Paper 1). We found that because of retardation of the Brilliant Blue dye the main change in moisture content did not coincide with the dyed areas. The GPR data and dye staining patterns both highlighted that water had moved very fast in certain parts of the subsurface. Laboratory and field studies have been carried out in which reflection GPR has been used to monitor the development of moisture content due to infiltration of tracer water but the literature on the subject is somewhat sparse (c.f. Trinks et al., 2001; Truss et al., 2007). Schmalz et al. (2002) presented results of a laboratory experiment, in which water was infiltrated into a sand-filled tank and monitored using reflection GPR data. They compared the amplitude variations in GPR data to moisture content variations in synthetically derived hydrological models with either homogeneous or randomly distributed hydraulic parameters. Infiltration of a dye tracer revealed that fingered flow occurred and the authors found that the model with randomly distributed hydraulic parameters best represented the results from the laboratory sand box (Schmalz et al., 2002). However, in natural geological settings sand bodies will contain structure and spatial correlation because of the processes, under which they were deposited. In Paper 4, we therefore used knowledge about the spatial correlation structures of the subsurface to set up the synthetic models, rather than assume random distribution of hydraulic parameters. This approach is in line with the findings of e.g. Biteman et al. (2004), who found that a groundwater model, in which the hydraulic parameter distribution was constrained by geological knowledge, was better at simulating tracer breakthrough.

In many cases the purpose of performing tracer experiments and monitoring the moisture content and/or conductivity development using cross borehole geophysical methods is to calibrate hydrological models and identify (site-specific) hydraulic parameters. Stressing the hydrologic system by adding unnatural amounts of tracer is required if it is assumed that monitoring natural conditions does not explore the different states of the hydraulic variables adequately (Binley et al., 2010). Numerous studies of such experiments carried out in different geological settings are reported in the literature (c.f. Binley et al., 2002a, Deiana, 2008, Looms et al., 2008, Doetsch et al., 2010). Binley et al. (2002a) injected a water tracer in unsaturated sandstone and used GPR and ERT to monitor the development of the arising plume. The spatial moments were then used for calibrating a hydrological model and estimate the saturated hydraulic conductivity. Similar experiments in which tracers are injected and monitored using GPR/ERT have been carried out by others, for example Deiana et al. (2008), who performed a tracer injection through a trench in unsaturated sandy sediments and used the results to calculate the saturated hydraulic conductivity at the site. Looms et al. (2008), on the other hand, stressed their system (at Arrenæs) by infiltrating water across a large area instead of as a point source, which had not previously been done. In order to obtain transport parameters from spatial moment analysis they assumed that flow could be considered uniform and one-dimensional at the site, since the subsurface consists entirely of sand. Unfortunately, it was not possible to assess whether the assumption of one-dimensionality was valid or not because their data suffered from severe mass balance problems.

The development of the injected tracer described in Paper 2 was also heterogeneous, but we did not have the same mass balance problems as those reported by Looms et al. (2008), although both experiments were carried out at Arrenæs site B, see Figure 3. In the area infiltration at Arrenæs (which was done on site C, Figure 3), however, we see that although the GPR ZOP data showed very
different infiltration patterns the mass balance did add up (as long as the wetting front was above the lower extent of the boreholes). Further, the synthetic three-dimensional modeling presented in Paper 4 suggests that an assumption of homogeneous, one-dimensional flow is valid for the Arrenæs site because spatial correlation lengths are relatively large. In the ERT data from Voulund we find indications of heterogeneous wetting front behavior, but assuming that the correlation lengths are also large at this site, the assumption of one-dimensionality is expected to be valid for this site as well.

In a recent review of hydrogeophysics and its opportunities and challenges (Binley et al., 2010), the authors conclude that lithologic and geologic information is crucial for accurate use and interpretation of hydrogeophysical data. We have seen direct evidence of this at Arrenæs (Paper 2) where grain size differences helped explain complicated flow patterns. Likewise, at Hjelm Hede (Paper 1) it was also clear that chemical differences in homogeneous sediments have great impact on infiltration and can initiate preferential flow in the unsaturated zone. A very recent (unpublished) study, in which CO₂ gas was injected into saturated sandy sediments, revealed that migration of the CO₂ gas was highly influenced by what seemed to be only minor changes in grain size composition (Lassen et al., 2014). When gas was injected into the aquifer at depth, it migrated upwards as a well-defined plume until encountering an interface to a finer layer. Upwards movement was subsequently halted and the gas instead moved laterally. This behavior of gas in the saturated zone is comparable to what we saw at Arrenæs for water injected as a point source into unsaturated sandy sediments (Paper 2), and further underlines that the behavior of the moving phase in complex three-phase systems consisting of air/gas, water and solid are inherently difficult to predict. In contrast to this stands the notion that in geological settings in which the unsaturated zone consists of predominantly sand and spatial correlation lengths are high, it may be justified to adopt a one-dimensional modeling framework for most purposes.

The results of the point injection experiment at Arrenæs showed that a few thin layers of increasing grain size were seemingly responsible for diverting water flow and causing the plume development to become highly heterogeneous (Paper 2). Likewise, the moisture content profiles from GPR ZOP data obtained during the area infiltration experiment at Arrenæs showed that flow became more heterogeneous after the tracer front reached depths where grain size distributions are less uniform across the area (Paper 4). During the tracer experiment at Voulund numerous GPR data sets were acquired, both as one-dimensional ZOP data and two-dimensional MOG data. Analysis of GPR data might reveal similar moisture content developments as for the experiments from Arrenæs, since the changes in grain size are comparable between the two sites. The degree of irregular flow might even be more pronounced at Voulund, however, since the results of the synthetic modeling in Paper 4 suggest that a stressed system behaves more homogeneously than an unstressed system. The assumption of homogeneity at Voulund (which was the basis for our recharge calculation), however, is still expected to be valid, since the recharge estimation was in line with measurements from the nearby lysimeters, and because the spatial correlation structures are expected to be large at the site.

Cross-borehole geophysics has been widely used for assessing moisture content in the unsaturated zone under natural and stressed conditions. Using GPR and ERT to monitor the natural variations in moisture content for better understanding of recharge processes to a sandstone aquifer was explored by Binley et al. (2002b), who estimated travel times of seasonal wetting fronts based on changes in
moisture content derived from the resistivity and radar measurements. So far, no studies have been published in which actual recharge is calculated based on a tracer experiment similar to the one carried out in Voulund (Paper 5). The ERT results agree with core sample measurements and the recharge estimate matches lysimeter drainage measurements. Since field site installation is less invasive and data acquisition relatively easy, it can be argued that cross-borehole geophysics could be used at other field sites for estimation of recharge instead of the much more difficult lysimeter installation. Evidently, the applicability of the method ultimately depends on e.g. the depth to the groundwater table, unsaturated zone lithology and the natural temporal moisture content changes. Also, the applicability depends on whether it is fair to assume vertical flow, which could be justified by determining the spatial correlation lengths at the site. If the methodology of Looms et al. (2010) is adopted the spatial correlation lengths can be determined using the two-dimensional GPR MOG data that have already been collected from the site.

For the recharge calculations described in Paper 5 we used moisture content measurements from the obtained cores in the calculation of solute conductivity. However, previous studies such as Winship et al. (2006) and Looms et al. (2008), used moisture content estimations from borehole GPR measurements for this purpose, which is also possible in the Voulund tracer experiment since GPR data from the experiment period exist. Moreover, application of full-waveform inversion of the GPR data could provide an additional measure of the electrical conductivity in the subsurface, from which a recharge value could also be estimated. In this way, using both ERT and GPR measurements for the estimation of a recharge value is truly minimally invasive and could be applied at other field sites. Andreasen et al. (2013) estimate regional groundwater recharge in the Skjern River Catchment using data from 20 soil moisture network stations. A similar number of cross borehole installations would be a lot and (particularly GPR) data acquisition would be cumbersome. However, the results from the soil moisture networks could point to a number and perhaps placement of a few extra borehole field installations, for which recharge values could be estimated using the same methodology as that in Paper 5. Comparing and combining such results with the data from the soil moisture network could provide a much more confident estimate of recharge, which could be used in large scale hydrological modelling of the Skjern River Catchment.

Conclusion

The experiments presented in this thesis were all carried out at field sites where the unsaturated zone consists of sandy alluvial sediments. Specifically, Voulund and Hjelm Hede are both situated on glacial outwash plains, a type of geological setting found in many other areas around the world, particularly in the northern hemisphere, which have been shaped by the previous glaciations. In the eastern part of Denmark, however, the upper layers of soil consist for the most part of moraine sediments deposited underneath or very close to the glaciers. Therefore, the findings presented here are more relevant for the western part of Denmark.

Water flow in the unsaturated zone is a complicated matter. Much effort has been put into visualizing and describing preferential flow phenomena on different scales and for many different geological settings. Geophysical methods such as surface reflection GPR have been shown to be able to also visualize irregular flow, although not with the same level of detail as, for example, dye staining
experiments. In the Hjelm Hede experiment we saw that the lack of flow detail was made up for by the sensitivity of the GPR method to the moisture content, which provided important information about where the water actually was, and not where it had been. In borehole configuration, the GPR method does not suffer from resolution loss at depth and can therefore be used for detailed investigations of e.g. natural moisture content development as well as moisture content changes arising from forced infiltration or point injection of tracer. This applicability was demonstrated in the two tracer experiments performed at Arrenæs, in which the GPR data allowed for a detailed analysis of the different flow processes taking place in the unsaturated zone.

Cross-borehole ERT is also a powerful method for monitoring tracer movement, although results suffer from a lack of detail, particularly in the case of point injection experiments, due to (necessary) regularization in the applied inversion routine. We applied the ERT method in an experiment aimed at estimating recharge from an area tracer infiltration and here it provided very useful results, which were corroborated by soil sample measurements from cores and lysimeter drainage data. Future analysis of the GPR data collected during the Voulund tracer experiment could shed further light on the moisture content development as well as provide an alternative estimate of recharge for comparison with the ERT derived result.

Common for cross-borehole GPR and ERT is that both methods are minimally invasive because they only require the drilling and installation of boreholes. Furthermore, when a new borehole array is established it is in many cases relatively easy with modern equipment to obtain a drill core from (at least one of) the boreholes. Preliminary analysis of such cores regarding lithology, moisture content and perhaps chemistry could prove to be very important as an aid in determining which type of measurements should be obtained, and also for interpretation of the cross-borehole geophysical data.

It is often assumed, for simplicity, that flow in the unsaturated zone can be considered vertical and one-dimensional and that any variation can be accounted for by a dispersivity value chosen based on a rule-of-thumb. Our results show that although grain size differences cause diversion of water and initiates irregular flow even in seemingly homogeneous sandy sediments, it is fair to assume one-dimensionality, provided the spatial correlation lengths are large. Such a finding can be important for hydrological modelling purposes and provide the empirical background for simplifying the unsaturated zone in large-scale (catchment) models. This is already being done extensively based on a notion that “over time and on large scales, the net transport of water/solutes in the unsaturated zone is vertical”. In many geological settings, the horizontal spatial correlation lengths are large because of the depositional history of the material. However, to extend the applicability of our findings, it is necessary to expand the analysis to also include hydraulic parameterizations that represent other geological settings than strictly unconsolidated sand. For example, the presence of a (thin) coherent impermeable layer that causes a high degree of lateral flow may invalidate our conclusions. Finally, it should be noted that although the results presented here suggest that unsaturated zones consisting of predominantly unconsolidated sand can for the most part be considered homogeneous, such an assumption will depend on the purpose of the study.
Acknowledgements

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Papers


(Paper 1 was included in E. B. Haarder’s M.Sc.-thesis in a preliminary version and was elaborated and finalized during the Ph.D. study period)


Visualizing Unsaturated Flow Phenomena Using High-Resolution Reflection Ground Penetrating Radar

Unsaturated flow phenomena, such as unstable wetting fronts and preferential flow, cannot be investigated using small-scale sampling. Dye tracer experiments can help visualize the dynamics of water flow but are destructive and therefore irreproducible. We investigated the applicability of high-resolution ground penetrating radar (GPR) for nondestructive visualization of unsaturated flow patterns arising from a forced infiltration experiment. Synthetic studies using a reflection GPR two-dimensional finite difference time domain modeling code indicated that differences in water content caused by preferential flow and fingering could be resolved. Moisture content contrasts down to approximately 2.5% within the top 2 m were detectable, but with increasing degrees of heterogeneity in the subsurface it becomes difficult to distinguish these moisture content changes. We conducted a field experiment in which 100 mm (900 L) of Brilliant Blue dyed water was infiltrated across a 3-by-3-m area in relatively homogenous and undisturbed sandy alluvial sediments. Reflection GPR data were collected before and after infiltration. Dye-staining patterns, revealed by excavating a 2-m-deep trench through the infiltration area, were compared with changes in the GPR data. Reflection amplitude changes as well as reflection delay revealed significant differences within the dye-stained area. The GPR data provided information about the unsaturated flow below the extent of the dye staining, and the results of the synthetic GPR modeling, as well as the observed changes in the real GPR data set, underline the potential of reflection GPR as a nondestructive method to map unsaturated flow phenomena.

Abbreviations: BB, Brilliant Blue; GPR, ground penetrating radar; TDR, time domain reflectometry.

The quality and quantity of groundwater resources depend highly on the flow and transport properties of the unsaturated zone. Traditionally, unsaturated hydraulic parameters are estimated using retention and hydraulic conductivity experiments performed on small soil samples in the laboratory. These small-scale analyses are not able to describe preferential flow paths or unstable wetting fronts that are observed at the field scale. Prediction and characterization of flow in the unsaturated zone was found to be difficult and highly complex in several studies using dye tracers for visualization of flow paths (Flury et al., 1994; Schmalz et al., 2002; Weiler and Flühler, 2004). Large-scale experiments on both homogeneous and heterogeneous soil columns have shown that fingering and preferential flow exist and dominate the flow field for soil types ranging from clayey soils to unstructured sandy sediments (Flury et al., 1994; Wildenschild et al., 1994, Schmalz et al., 2002). Simůnek et al. (2003) and Kung (1990) furthermore showed that the infiltration of water seemed to be dependent on the dip of geologic layers and that the dipping layers could also induce fingered flow.

Dye tracing infiltration experiments are powerful techniques for visualizing the dynamics of unsaturated water flow and have been widely used for many purposes (Flury and Wai, 2003). The popularity of Brilliant Blue as a dye tracer is attributed to its excellent visibility in most soil types, its nontoxicity, and its solubility in water (Flury and Wai, 2003). Brilliant Blue has been found to be subject to retardation because of nonlinear absorption, and, in consequence, it cannot be considered an ideal, conservative tracer (Kasteel et al., 2002). Thus Brilliant Blue is not suitable for the estimation of water flow properties but is ideal for illustrating water flow pathways in soils.

A major drawback in using dye tracing for unsaturated flow characterization is that the method is destructive and unrepeatable at the same location because the survey area needs to be excavated and the method therefore only provides a snapshot of the flow. Alternatively,
Materials and Methods

Ground Penetrating Radar

Ground penetrating radar wave velocity and signal attenuation depend on the relative dielectric permittivity, \( \varepsilon \), magnetic permeability, \( \mu \), and electrical conductivity, \( \sigma \), of the subsurface as well as the frequency of the signal (Davis and Annan, 1989). The magnetic permittivity is often disregarded in nonmagnetic materials such as sandy sediments.

The dielectric constant can be related to the electromagnetic wave velocity, \( v \), in the following manner for low-loss geologic materials (Davis and Annan, 1989):

\[
\sqrt{\varepsilon} = \frac{c}{v} \tag{1}
\]

where \( c \) is the speed of light. If the electromagnetic wave velocity or dielectric properties are known, the moisture content of a given subsurface can be calculated using the empirical relationship of Topp, which relates moisture content \( \theta \) to the dielectric constant (Topp et al., 1980):

\[
\begin{align*}
\theta &= 5.3 \times 10^{-2} + 2.92 \times 10^{-2} \varepsilon \\
&- 5.5 \times 10^{-4} \varepsilon^2 + 4.3 \times 10^{-6} \varepsilon^3
\end{align*} \tag{2}
\]

In this study, we used the simpler, approximate form of Topp’s equation developed by Ferré et al. (1996):

\[
\theta = 0.1181\sqrt{\varepsilon} - 0.1841 \tag{3}
\]

which has been shown to provide results that differ <5% from Topp’s original equation for volumetric water contents between 5 and 40% (Ferré et al., 1996).

Contrasts in dielectric properties of the subsurface cause parts of the emitted electromagnetic signal to reflect back to the receiver at the surface (Davis and Annan, 1989). Following Eq. [1] and [2], water in a porous material lowers the electromagnetic wave velocity by increasing the dielectric constant. Abrupt changes in moisture content produce high reflection coefficients because of large GPR wave velocity differences, and these show up in the resulting radargram as reflections.

The vertical resolution depends on frequency and bandwidth, and can be approximated by one quarter of the pulse length (Reynolds, 1997). The horizontal resolution depends on the antenna radiation pattern and signal frequency, and decreases with depth as the radius of the first Fresnel zone increases and the signal moves downward in a conical beam of increasing width (Reynolds, 1997). Migration can improve the horizontal resolution, however, by focusing the signal and restoring true reflection dips (Yilmaz, 1987; Grasmueck et al., 2005).

Field Site

For this study, we chose a heath area, Hjelm Heath, situated in the northern part of Jutland in Denmark (see Fig. 1) as the field site. The area was formed as a glacial outwash plain during the last phases of the Weichselian glaciation when large amounts of meltwater were released from the melting glaciers and deposited tens of meters of meltwater sediments, predominantly sand (Houmark-Nielsen et al., 2005). A geologic setting such as this is very common for the western part of Denmark, where most of the sandy soils are used for agriculture.

The vegetation cover at the site consists of heather [Calluna vulgaris (L.) Hull], wavy hair grass [Deschampsia flexuosa (L.) Trin.],
Fig. 1. Overview of field site: schematic of the ground penetrating radar (GPR) area, infiltration area, excavations, and sample collection—the infiltration area covers Trace 15–75 in GPR Lines 10–70 (top); and picture from field campaign during acquisition of post-infiltration GPR data (bottom).

The infiltration experiment was inspired by the works of Flury et al. (1994), Javaux et al. (2006), and Kung (1990), who performed infiltration experiments using BB as a tracer. Flury et al. (1994) infiltrated 40 mm of BB-dyed water (concentration 4 g/L) in 14 different soil types and found that after 8 h, the penetration depth was in many cases considerably <1 m but that for some soils extreme bypassing was seen. Javaux et al. (2006) infiltrated 180 mm of BB-dyed water (concentration: 1 g/L) into a 1-m sand column and within 8 h the dyed water had not reached the maximum depth.

We chose to infiltrate a total amount of 100 mm (900 L) of BB solution during 2 h across an area of 3 by 3 m. Watering cans equipped with simple sprinklers for more uniform spreading of the water were used for water application. After infiltration, the area was left uncovered, and a small rain shower delivered a couple of millimeters of precipitation during the night, which was negligible compared with the infiltrated 100 mm. Evapotranspiration was of no significance because the infiltration experiment was conducted in early April, at which time evapotranspiration is low. One day after infiltration, a trench was excavated through the infiltration area to a depth of 2 m for visual assessment of the dye tracing patterns outlined by the BB dye (see Fig. 1 for location and extent of trench excavation). Table 1 summarizes the timing of events in the infiltration experiment.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>2 Apr. 2008</td>
<td>0800</td>
<td>soil removal</td>
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<tr>
<td></td>
<td>1000–1300</td>
<td>collection of GPR preinfiltration data set</td>
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<tr>
<td></td>
<td>1430–1630</td>
<td>infiltration of BB solution (100 mm across 3-by-3 m area)</td>
</tr>
<tr>
<td></td>
<td>1730</td>
<td>1–2 mm of precipitation</td>
</tr>
<tr>
<td>3 Apr. 2008</td>
<td>0830–1130</td>
<td>collection of GPR post-infiltration data set</td>
</tr>
<tr>
<td></td>
<td>1300</td>
<td>excavation commenced</td>
</tr>
<tr>
<td></td>
<td>1600</td>
<td>soil samples collected in excavated trench</td>
</tr>
</tbody>
</table>
Ground Penetrating Radar Data Acquisition

Ground penetrating radar lines were collected using a PulseEKKO Pro System (Sensors and Software, Mississauga, ON, Canada) equipped with shielded 250-MHz antennas and an odometer wheel for trace spacing measurements. We used the following acquisition parameters: time window, 500 ns; stacking, 16; sampling interval, 0.4 ns. For precise data collection, we constructed a setup consisting of two hollow polyvinyl chloride slides along which the GPR instrument was pulled. Before carrying out the actual field work, it was verified that the slides did not adversely affect the GPR data collected by the shielded antennas. The slides were 10 by 10 by 600 cm and were manually fixed to the ground by bamboo sticks in order not to obscure the data collection. Careful repositioning of the GPR instrument for each line along the slides assured that the repeated data sets were comparable line to line.

Before and after infiltration, a total of 100 GPR lines were collected with a line spacing of 0.05 m (see Table 1 for timing of data collection). For all lines, the trace spacing was also 0.05 m, thus providing a uniformly sampled three-dimensional data set. Each line consisted of 94 traces, making the final data acquisition area 4.95 by 4.65 m (23.02 m²). Because BB dye was infiltrated over a 3- by 3-m area within the GPR area (see Fig. 1), the GPR data set collected after infiltration contained lines both affected and not affected by direct infiltration. Also, each GPR line crossing the infiltration area had several traces at the beginning and end that were not affected by BB infiltration. For details of the field site layout, see Fig. 1.

The GPR signal was delayed and attenuated by the extra amount of water (Reynolds, 1997; Truss et al., 2007) and the higher conductivity of the infiltrating BB solution further attenuated the signal. In areas of relatively high electrical conductivity, the conductivity of the studied formation may significantly affect the velocity and the validity of the relations based on the low-loss criteria such as Eq. [1–3] (Giroux and Chouteau, 2010). For the amount of conductive BB solution that we applied in this experiment, however, we assumed that these effects related to the bulk conductivity of the studied formation were negligible and thus we assumed that any decrease in velocity was merely due to an increase in moisture content. There is a chance that some reflections were more pronounced due to ponding of water at geologic boundaries, which would cause the reflectivity coefficient to increase.

Ground Penetrating Radar Data Processing

The collected GPR data were processed using the EKKO View Deluxe and MATLAB (MathWorks, Natick, MA) software packages. For all lines, a dewow correction was applied as the first step in the processing to remove low-frequency noise. Pre- and post-infiltration GPR lines were then plotted in MATLAB and the same simple scaling function was applied to all lines. The individual GPR data lines were migrated (two-dimensional migration) using the EKKO View Deluxe software to remove diffraction hyperbolas and focus the signal. The same migration velocity was applied to the pre- and post-infiltration data sets. For detailed analysis of single reflections in the GPR data, MATLAB was used to pick reflections in all lines for both data sets, thus obtaining the arrival time and amplitude for each reflection in the entire data set. The arrival time differences could then be translated into electromagnetic wave velocity changes and converted into approximate moisture content changes using Eq. [3] and information about the thickness of the geologic layers obtained from the excavated profiles. Analyses of multiple reflections provided a basis for estimating the spatial distribution of the water in the subsurface and could potentially be validated against the BB dye-staining patterns.

Synthetic Studies

Configuration of Synthetic Models

To evaluate the possibilities and limitations of using reflection GPR to monitor unsaturated flow phenomena, a synthetic analysis was performed using the MATLAB-based two-dimensional finite-difference time-domain (FDTD) code developed by Irving and Knight (2005). Synthetic subsurface models are defined by specifying distributions of electrical conductivity, as well as dielectric permittivity and magnetic permeability. The two-dimensional FDTD code uses a source pulse, which is the normalized first derivative of a Blackman–Harris window function (Irving and Knight, 2005). Any type of synthetic model can be created and modeled using the code; however, the computation time increases with the complexity of the chosen synthetic model and model discretization.

We created a synthetic geologic model of 10-m depth and 20-m width for Hjelm Heath based on TDR measurements as well as soil samples extracted during installation of the TDR well at the field site (Ladekarl et al., 2005; Rasmussen, personal communication, 2008). Dielectric permittivity values used in the model were calculated based on soil moisture measurements from the nearby TDR well. The subsurface part of the model consists of four layers that have different values of $\varepsilon$ ranging from 4 to 6 corresponding to moisture content values between approximately 0.05 and 0.12, respectively. An air–earth interface was included by adding a layer with relative dielectric permittivity $\varepsilon = 1$ and electrical conductivity $\sigma = 0 \text{ S/m}$ to the top of the model. Because, for simplicity, we were mainly interested in the delay of reflections, the conductivity was set to $\sigma = 0.001 \text{ S/m}$ and the relative magnetic permeability was represented by its free-space value, $\mu = 1$, throughout the model. During a real forced infiltration experiment, changes in electrical conductivity are expected to occur, caused by both the added amount of water and the potentially different electrical conductivity of the infiltrated water (compared with the incipient soil water). Thus, the amplitude variations and attenuation of the
modeled signal in the synthetic tests were not affected as much as during a true infiltration experiment.

We chose simulation parameters closely resembling the real GPR equipment used in the field experiment. The signal had a center frequency of 250 MHz, the spacing between the transmitter and receiver was set to 0.4 m, and the simulations were made with a constant offset. The model discretization was 0.02 m.

To recreate an infiltration event, we included a wetting front from 0 to 1.5 m with increased moisture content (0.025 higher than the underlying layer) in the synthetic model. The middle of the infiltration was shaped like a 2-m-wide and 1-m-deep channel to simulate an unstable wetting front causing fingered flow (Fig. 2A). Because lateral flow was also likely to occur, another model containing a wedge-shaped area of increased moisture content was also created (Fig. 3A). Synthetic GPR radargrams were calculated only for a 2-m-wide subsection of the model, which is marked in Fig. 2A and 3A by the vertical dotted lines.

We assumed the spatial variability of moisture content and thus the dielectric permittivity to vary within each layer. Spatial variability was added to the input dielectric permittivity model as normally distributed and spatially uncorrelated random noise with standard deviations of 0.25 and 0.50, respectively. This amount of random noise corresponds to heterogeneity in the moisture content of up to 1.5%. Figures 2B to 2D and 3B to 3D show the variation in dielectric constant with depth for the three input models. We see how the change in dielectric constant, and thus in moisture content, becomes more diffuse when more heterogeneity is added.

Fig. 2. Synthetic ground penetrating radar (GPR) data: (A) dielectric permittivity background model with channel-shaped infiltration “finger” (dotted lines mark the part of the model for which the GPR simulation was run and the solid black line marks the position of the moisture content profiles); moisture content profiles (B) without heterogeneity in the dielectric permittivity model and with heterogeneity standard deviations of (C) 0.25 and (D) 0.50; and (E–G) the resulting synthetic radargrams for each degree of heterogeneity (solid arrows indicate the position of the bowtie and dotted arrows indicate the delay of deep reflection).

Fig. 3. Synthetic ground penetrating radar (GPR) data: (A) dielectric permittivity background model with wedge-shaped infiltration (dotted lines mark the part of the model for which the GPR simulation was run and the solid black line marks the position of the moisture content profiles); moisture content profiles (B) without heterogeneity in the dielectric permittivity model and with heterogeneity standard deviations of (C) 0.25 and (D) 0.50; and (E–G) the resulting synthetic radargrams for each degree of heterogeneity (arrows indicate diffraction features below wedge).
It should be noted that all the synthetic analyses in this study were made using a two-dimensional code, the underlying assumption being that the constructed subsurface models continue indefinitely perpendicular to the presented image. Thus, “fingers” are more like trenches than cylinders. Wave scattering is expected to increase in true three-dimensional environments, and consequently the findings presented here are therefore perhaps overly optimistic, yet they give an indication of what changes we can expect to observe.

Results
Figures 2E to 2G show the resulting synthetic radargrams that contain increasing degrees of heterogeneity within the subsurface for models with a channel-shaped increase in moisture content. If the subsurface is assumed not to be subject to internal variation in moisture content within each layer, the resulting synthetic radargram for the infiltration finger will show a distinct bowtie structure arising from its channel-like shape (cf. Yilmaz, 1987). This effect can be seen in Fig. 2E, marked with an arrow. Likewise, the wedge causes diffraction hyperbolas along its bottom (Fig. 3E, marked by an arrow).

In Fig. 2F, we see that for the lowest degree of added heterogeneity the bowtie structure is still visible in the resulting radargram (marked with an arrow). With the addition of more heterogeneity, the bowtie became more diffuse (Fig. 2G). The larger heterogeneity also made the deeper reflections harder to recognize. Figures 3F and 3G show the resulting synthetic radargrams that contain increasing degrees of heterogeneity within the subsurface for models with a wedge-shaped increase in moisture content. Even with a low amount of added heterogeneity, the extent and shape of the wedge becomes hard to distinguish, and as the heterogeneity increases, the wedge disappears almost completely.

For the infiltration finger, we observed delays of up to 2 ns and a changed dip of deeper reflections due to the increase in moisture content in the top of the model (marked with a dotted arrow in Fig. 2 for the lowest reflection). Even with strong heterogeneity that blurred the shape of the water front, these effects did not disappear and can thus provide information about the infiltration, even in cases where the direct effect cannot be seen. It can also be seen that the parts of the deeper reflections that were affected by the increase in moisture content in the infiltration finger had a greater lateral extent than the actual finger. This was due to the radiation pattern and Fresnel resolution of the signal and means that changes in the radargrams at depth are likely to represent actual changes on a smaller scale at shallower depths.

The increase in moisture content of 0.025 used for this analysis was assumed to be low, and for larger increases the infiltration finger would be more easily recognized, even in the case with large heterogeneity. Based on the results of the numerical modeling, we expect to be able to delineate the bulk changes in moisture content arising from a forced infiltration experiment using reflection GPR. In the case of a moisture content increase in large coherent volumes of the subsurface, it should be possible to see attenuation of the signal in the wet areas (not shown). The type of information that can be achieved through the GPR data is, however, dependent on the amount of heterogeneity in the subsurface.

Sedimentary Structures
The main excavation was a trench dug to a maximum depth of 2.2 m through the middle of the BB-dyed area (see Fig. 1). Only one side of the excavation was kept as a vertical profile, which can be seen in its full length and depth in Fig. 4. The top of the profile was approximately 45 cm below the soil surface due to the removal of the topsoil and hard pan at the site. Figure 5 shows details from both vertical profiles as well as horizontal excavations.

The vertical profile reveals that the uppermost subsurface at Hjelm Heath consists of several different sedimentary packages of sand with varying grain sizes and structures. This concurs with grain size analysis results from the field site reported by Ladekarl et al. (2005).

The top 0.20 m of the excavated profile consists of sand that is highly disturbed by bioturbation and root remnants (Fig. 4, marked A), but it is still possible to distinguish cross-bedding. Ladekarl et al. (2005) reported that the active root zone at Hjelm Heath extends to 60 cm below the surface, i.e., only 15 cm into the excavated profile; however, the vertical profile reveals root structures to a depth of 0.5 m (i.e., 0.95 m below surface). These deeper root remnants are characterized by having black, hardened centers and are up to 5 cm in diameter. Because the active root zone only extends to 0.60 m below the surface and the deeper root remnants have been severely altered, it is believed that they are ancient tree roots >1000 yr old) from before deforestation of Western Jutland began (Andersen, 1994).

![Fig. 4. The main vertical excavation. The profile is approximately 2.2 m deep and 4 m wide. The blue arrow indicates the extent of infiltration at surface. Also indicated are active roots and bioturbation (A), redoximorphic horizon (B), bypassed areas (C), infiltration fingers (D), lateral flow (E), and isolated dyed areas (F).](image-url)
From 0.2 to 2 m in the excavated profile, the sediments are planar with a slight dip of approximately 2° toward the southeast. At the 1.4- to 1.5-m depth, we found a horizon with a dark orange color, probably stemming from precipitated Fe oxides (Fig. 4, marked B). This process is known as redoximorphism (Jacobs et al., 2002), which occurs when the groundwater table is both high and fluctuating. As such, this horizon is expected to have originated from the time around the last glaciation, when permafrost forced the groundwater upward during the winter (Jacobs et al., 2002). Due to redoximorphism, Fe precipitates, seen as orange nodules, are much more prevalent below the horizon than above.

Around the 2-m depth, there is a transition from planar to cross-bedded sediments as well as a decrease in grain size. The interface between the two sedimentary packages dips toward the northwest; this is best seen in Fig. 5A, marked 1.

**Dye-Staining Patterns**

Dye-staining patterns arising from the infiltration experiment can be seen in Fig. 4 and 5. In Fig. 4, the blue arrow indicates the extent of the infiltration at the surface. Note that the edges of the profile have not experienced infiltration.

We observed that the top 1 m of the profile below the infiltrated area was almost entirely blue due to dye staining, although areas existed within the top 1 m where bypass flow had occurred, as in Fig. 4, marked C. Below the 1-m depth, the dye-staining pattern became more irregular and uniform matrix flow appeared to no longer be the dominant flow process. In the middle of the profile, we observed three large flow fingers (Fig. 4, marked D) that had facilitated the deepest dye infiltration. The fingers had a maximum width of 0.2 m in the excavated plane; however, their three-dimensional structure was not revealed by the main excavation. Sedimentary structures within the large fingers did not reveal any variation that would make them more prone to water flow; however, they appeared to initiate at the same depth as the redoximorphic horizon. The precipitates probably prevented flow across sections of the horizon, causing the infiltrating water to break through a few permeable windows, forming infiltration fingers.

Toward the edges of the infiltration area, water had infiltrated laterally to the sides (Fig. 4, marked E). Detailed inspection of the dye-staining patterns revealed that BB-stained water had moved along small sedimentary or structural boundaries in the layered sediments. The irregularity of water flow was in part initiated by grain size differences in the sand acting as small capillary barriers, as illustrated in Fig. 5B. Small-scale flow along horizontal or dipping boundaries between changing lithologies, as well as diffusive flow, can thus be responsible for transport of water out of the infiltration area.

With the purpose of investigating the three-dimensional nature of the infiltration patterns, we removed 0.3 m of sediment from the central 1 m of the main profile (for exact location, see Fig. 1 and 4). The 1-m-wide and 2-m-high profile can be seen in Fig. 5A. Brilliant Blue dye staining in the top 1 m of this profile was less coherent compared with Fig. 4, with almost a third of the area completely undyed. The large unstained or bypassed area in the top of the profile was caused by the presence of an ancient root (Fig. 5A, marked 2), which diverted the water flow. In the horizontal view, some of the ancient roots appeared as circular black structures with a periphery of undyed sand around them, suggesting hardening of the surrounding sand due to precipitation of organic matter (see Fig. 5C). Although the black root remnant in Fig. 5A extended 0.25 m into the profile, the surrounding sand continued to be bypassed to a depth of 0.65 m below the profile top.

Isolated patches of dyed sand were found in numerous places in the profile (see Fig. 4, marked F) and further illustrate the heterogeneous nature of the infiltration. Notice also that the three large infiltration fingers seen in the main profile (Fig. 4, marked D) are not visible at this position. Rather, there is one large wide infiltration path to the right, which seems to extend below the depth of the excavation.

The “floor” of the excavation pit at the 2-m depth revealed large blue stains (not shown here), indicating that there had been percolation...
of infiltrated water deeper than 2 m into the subsurface, which was not visualized by the dye-staining patterns in the main profile.

The overall infiltration patterns seen in the excavation at Hjelm Heath are similar to the flow type “heterogeneous matrix flow and fingering” as defined by Weiler and Flühler (2004), with most of the fingers being rather large in diameter with a high connectivity between the dyed areas. The bypass of large areas at the top of the profile caused unstable flow, disrupting homogeneous infiltration. This was further accentuated by the slightly hardened redoximorphic horizon that created infiltration fingers.

Ground Penetrating Radar Data

Figure 6A and 6C show the raw and migrated preinfiltration GPR Line 44, respectively. A two-dimensional migration velocity of 0.125 m/ns was chosen based on the average soil moisture measurements from the nearby TDR. The 100 preinfiltration GPR lines show the same overall distribution of reflections in the subsurface, which can be divided into three sections. The top section consists of parallel reflections dipping slightly toward the southeast, which corresponds to the planar bedding found in the top 2 m of the excavated profile. Below the parallel reflections, we find a more heterogeneous collection of less continuous reflections, with several distinct dipping reflections across the entire profile (Section 2). In the unprocessed data, this feature appears as a bowtie (c.f. Yilmaz 1987), yet in the migrated lines it resembles several generations of a buried river channel. Due to the short length of each line, however, it is generally difficult to determine what this relatively deep feature really is.

Several reflections can be recognized with a high degree of connectivity throughout the entire data set. From Section 3 and below, the reflections become less pronounced and the radargrams are mostly dominated by multiples and noise. The last horizontal reflection in the bottom of Section 1 appears to fit the interface between the two textures of sand seen in the excavation at approximately the 2-m depth (Fig. 4 and 5A).

Figures 6B and 6D show the raw and migrated post-infiltration GPR Line 44, respectively, and also here we see that it is possible to distinguish the three sections. Five reflections have been marked in both the pre- and post-infiltration radargrams (Fig. 6C–6D). Furthermore, the outline of the dyed area in the main excavation has been superimposed onto the post-infiltration radargram.

Ground Penetrating Radar Signal Changes

An important observation in comparing unmigrated radargrams from before and after infiltration is that no new diffraction features are apparent after infiltration (Fig. 6B). We would expect large contrasts in moisture content to create diffractions and disturb the image of the subsurface following the synthetic analyses described above. Since we can clearly recognize reflections at depth after infiltration, this is not the case.

A closer look at the single traces of each radargram reveals that amplitudes for traces affected by infiltration are diminished after infiltration while traces from outside the infiltration area do not show the same tendencies. On several traces, especially the ones inside the infiltration area, the two data sets differ somewhat at
the very top, i.e., within the first couple of waveforms. This could be attributed to minor changes in the surface characteristics. To collect the GPR data sets during infiltration, it was necessary to walk within the experimental area, which probably affected the uppermost sediments. Furthermore, the surface was raked during infiltration, which surely disturbed the top few centimeters of sand. These effects, as well as the minor uncertainty accompanied by repositioning the GPR equipment along the slides can probably explain the difference in signals at shallow depths.

Inspection of GPR lines from within the infiltration area reveals that some reflections toward the middle changed and are less coherent and pronounced after infiltration. An example of this is pointed out in Fig. 6D (marked 1). Also, the signal around Reflection 4 in the middle of the radargram appears to have become attenuated after infiltration (Fig. 6D, marked 2). Both of these effects were probably due to the presence of infiltrated water.

Below Reflection 3 at approximately the 2.5-m depth, an otherwise incoherent reflection became more pronounced after infiltration. It is best seen in the unmigrated data, Fig. 6B, marked 3. This could be attributed to ponding of water on one side of a geologic boundary, thus causing the reflection coefficient to increase due to the higher contrast in GPR velocity between the two media. Similar observations were not as pronounced in lines outside the infiltration area, which further indicates that the observed changes were caused by the infiltrated water.

In Fig. 6E, the five marked reflections from before and after infiltration are shown together. We see clearly how they were delayed, especially within the infiltration area, which is marked by dotted lines. As mentioned above, such a delay must be attributed to a change in moisture content between the pre- and post-infiltration data acquisitions. If the same comparison is made for reflections from lines outside the infiltration area, no delay is found, suggesting that the moisture content was unchanged.

The delays are most prominent for Reflections 3, 4, and 5, with Reflection 4 being the most delayed. This can partially be explained by the delay accumulating through the radargram but also indicates that the bulk amount of water had percolated through the top section and was now found at greater depths.

**Reflection Delay**

The arrival time and amplitude of the five reflections shown in Fig. 6C to 6E were selected out of the entire data set. The difference in arrival time for each reflection was subsequently calculated, and the result is illustrated in Fig. 7. For Reflection 1, Fig. 7A shows the delay for the entire volume between the surface and the reflection, whereas Fig. 7B to 7E represent the delay between each selected reflection and the previous one. Blue colors indicate delays. Due to the short length of each GPR line, the channel structure that constitutes Reflection 5 is not always well determined and therefore the results in Fig. 7E should be interpreted with caution. In spite of the inherent picking difficulties and apprehensions toward the reflection delay analysis, Fig. 7 shows continuous areas experiencing similar delays for the picked reflections that cannot be dismissed as errors.

The observed delay was mostly confined to the infiltration area, indicated by a black box in Fig. 7A to 7E. The delay of Reflection 1 is mainly found in the southern part of the area with no delay found in the northern parts; Reflections 2 and 3 were delayed across the entire infiltration area, and for Reflection 4 the delay...
was mostly concentrated in the northeastern part of the infiltration area. The large red areas in Fig. 7E illustrate how Reflection 5 was not further delayed compared with Reflection 4.

The delay also extended outside the infiltration area for the other reflections and could be caused by lateral flow, as was also observed in the dye-staining images (Fig. 4 and 5). It should be noted here that because propagation of the electromagnetic wave is three dimensional, the received signal represents a volume of the subsurface that becomes larger with depth (cf. Reynolds, 1997). A change in moisture content or conductivity within the infiltration area can thus give rise to changes in GPR signals emitted from the surface outside the infiltration area. Migration of the GPR data does not remove this effect entirely, although it will be less for shallow reflections.

The delay distribution between the different reflections and associated moisture content change can be correlated with the observations in the radargrams in terms of dipping reflections, as well as the sedimentary structures revealed in the excavation. Hence, the water movement at Hjelm Heath on this scale seems to be controlled by the dip of sedimentary structures in the subsurface.

In Fig. 7A to 7E, the position of the excavated trench is marked by a dotted line through the experimental area. We found that, based on reflection delays, there was almost no extra water present in the first ~1.5 m of the profile (i.e., down to Reflection 1) after infiltration. The profile revealed extensive dye staining of the sediments; however, the reflection delays indicated that the infiltrated water must have percolated beyond this depth.

**Moisture Content Measurements**

Ten soil samples were collected from the main profile for volumetric moisture content measurement (for exact locations, see Fig. 1). The samples were collected every 0.20 m, the first at a depth of 0.20 m from the top of the profile (i.e., down to Reflection 1) after infiltration. The profile revealed extensive dye staining of the sediments; however, the reflection delays indicated that the infiltrated water must have percolated beyond this depth.

The moisture content increased from $\theta = 0.05$ at the top to $\theta = 0.12$ at a depth of 2.45 m below the soil surface. The samples that were collected from the excavated profile ranged from being completely dyed to undyed; however, no connection could be made between the measured moisture content and the degree of dye staining.

Moisture content profiles obtained from TDR measurements in the nearby well are also depicted in Fig. 8 (Rasmussen, personal communication, 2008). We have included average as well as minimum and maximum measurements for the year 2008 as well as the average moisture content for the week in 2008 during which the field work took place. Note that the depth axis represents meters below the vegetated surface.

The TDR data show an increase in moisture content from 0.06 to 0.11 within the first couple of meters; thereafter it decreased to 0.05 between 2 and 2.5 m. The measurements after infiltration were in general slightly higher than the mean moisture content measured by the TDR probes during the field campaign. This difference could be caused by the forced infiltration experiment but could also arise from changes in soil properties between the two measurement points because there was approximately 20 m from the TDR well to the experimental area.

The largest difference in moisture content was found at the 2.45-m depth, where the samples showed moisture contents around 0.12 while the TDR data showed values of 0.05. Such an increase in moisture content should, according to the synthetic studies, affect the GPR radargrams substantially, which, however, was not the case. The TDR data have here been assumed to represent background values of moisture content for this area; however, it is possible that the background moisture content at the TDR profile was different from that of the field site due to changes in sedimentology. If, instead, an average moisture content increase of 0.02 due to the general tendencies seen in Fig. 8 is assumed, this change would not give rise to major changes in terms of diffraction effects in the GPR data.

**Amplitude Analysis**

An analysis of amplitude changes between the two GPR data sets can provide insight into the overall impact of the infiltration experiment on the GPR wave energy distribution. An increase in moisture content or conductivity near the top will attenuate the signal and cause increased changes with depth. As was the case...
with the reflection analysis, changes in the amplitude root mean square between the two data sets can be interpreted to represent changes in moisture content or conductivity.

Amplitude analysis was performed for the migrated data set in three intervals of the subsurface and the results are shown in Fig. 9. Each interval has been marked with different colors in Fig. 9D. The first section encompasses the entire signal above Reflection 1 (Fig. 9A, green in Fig. 9D), whereas the second and third intervals are considered between Reflections 1 and 2 (Fig. 9B, blue in Fig. 9D) and Reflections 2 and 4 (Fig. 9C, red in Fig. 9D), respectively. The first two intervals incorporate all the horizontal reflections in the top of the radargrams, whereas the third amplitude analysis interval contains the upper part of Section 2 (Fig. 6C).

Root mean square values were calculated from the amplitude values of each GPR line in the given time interval, and the difference between the before and after data set was calculated by simple subtraction. We used the arrival time of the specific reflections obtained previously to determine the upper and lower boundaries of the intervals of interest, thus automatically taking into account the time shifts occurring in the radargrams. This method renders results that merely show the change in GPR signal amplitude within the part of the subsurface between the two reflections delineating the analysis interval.

The outline of the infiltration area is shown in Fig. 9A to 9C as well as the position of the excavated profile (dotted line). Blue colors indicate that the signal has been attenuated, whereas reddish colors show areas where the amplitudes have increased after infiltration. For the analyzed intervals of the subsurface, it is evident that the GPR signal was subject to change primarily within the infiltration area but also up to almost 1 m outside the infiltration area. Note that the area influenced by changing amplitudes outside the infiltration area increased between the three sections. As mentioned above, part of this tendency can be attributed to the three-dimensional propagation of the electromagnetic waves, which caused lines outside the infiltrated area to be affected by the changes caused by the infiltration.

For the first interval, Fig. 9A, we found that the change in amplitudes was not particularly significant but that the decrease in amplitude was mostly confined to the infiltration area. This observation is consistent with the findings from the reflection analysis (Fig. 7), which showed that Reflection 1 experienced less delay than the other reflections analyzed. The small change in amplitude within the entire infiltration area of the first interval can be attributed to the increase in conductivity of the soil water caused by the BB dye present in the upper layers (as seen in the excavations, Fig. 4 and 5). It is apparent for the second and third intervals (Fig. 9B and 9C) that the main change in amplitude occurred within the infiltration area. It is also worth noticing that for all intervals the primary change within the infiltration area was toward lower amplitudes, i.e., an attenuation of the signal. An increase in amplitude is seen primarily along the edges of the infiltration area, which can be explained by lateral flow at the edges of the wetting front and subsequent increases in reflectivity at geologic boundaries just outside the infiltration area.

**Discussion**

Many previous studies have attempted to describe preferential flow paths and unstable wetting fronts. These investigations have rarely included moisture content measurements and subsequent...
assessments of the whereabouts of the infiltrated water. In Flury et al. (1994) and other studies, the soils were classified as either initially “dry” or “wet” but the actual moisture contents of these soils were not measured either before or after infiltration (Flury et al., 1994; Weiler and Flühler, 2004). Hence, the results of these studies merely illustrate the movement of the infiltrated dyed water and as such do not shed light on the overall movement of soil water in the surrounding subsurface.

Our results indicate that the excess water from the infiltration was not present in the dyed areas and that displacement flow was responsible for distributing the water farther into the subsurface. Moisture content increases were seen deeper than 4 m into the subsurface although the dye staining in the excavation was most prominent in the top 2 m of the soil. Whether BB dye in selected places had moved as far into the subsurface as the water is unknown because we only had visual assessment of the water and dye movement from the excavation. The observation of large stained areas in the bottom of the excavation, however, could be an indication of deeper infiltration of the dye.

According to the texture analyses performed by Ladekarl et al. (2005), the sand between 3 and 5 m is much coarser than the surrounding geology and contains much gravel compared with the other samples analyzed. The part of the subsurface between 3 and 5 m corresponds roughly to the radar signals between Reflections 4 and 5. Assuming that the geology also represents the experimental site used for the present study, this has two implications: (i) the coarser layer facilitated a much faster infiltration to deeper layers, which cannot be distinguished in the GPR data set beyond Reflection 5 because of noise, multiples, and loss of energy; or (ii) the coarser layer was acting as a large capillary barrier (because the general moisture content was still low) and thus water was moving laterally on top of this layer around Reflection 4. The latter is in agreement with the assumption that the water is likely to move along the geologic boundaries, as the reflection analysis also highlighted.

Compaction has been shown to induce preferential flow in sandy loams (Mooney and Nipattasuk, 2003), and as it was necessary to walk inside the infiltration area while the GPR data sets were collected and during infiltration, this could have caused a slight compaction of the upper sediments and thus influenced the infiltration. Cracks and small deformation could have caused the water to bypass some areas while flow could be facilitated in others, but on excavating the profile we did not find evidence that such compaction factors governed the overall water flow. Instead, we observed how ancient roots induced the bypass flow and that unstable flow and fingering was induced at a cemented horizon.

Assuming an average moisture content between 0 and 2 m of 0.075 before infiltration (value based on TDR measurements in Fig. 8), the amount of water in this volume would be 1350 L. The addition of 900 L of water through infiltration would increase the moisture content to 0.125, which was only measured in the deepest sample location (2.65-m depth). The reflection delays do not correspond to moisture content increases of this magnitude. If the average delay and depth of Reflection 2 based on the results from Fig. 7 are assumed to be 0.6 ns and 2 m, respectively, the increase in moisture content corresponds to an additional 200 L of water. This means that the remaining 700 L of infiltrated water has either moved laterally out of the area or percolated deeper. Because there was little evidence from either the excavation or the GPR reflection analysis that such large amounts of water had moved to the sides, it must be concluded that the infiltrated water had passed through to the subsurface beneath Reflection 2. This is also evident from the increasing delays of Reflections 3 and 4, which suggests that most of the infiltrated water was located between these reflections. Figure 7 also shows that the delay of Reflection 5 was less than that of Reflection 4, which suggests that there was no extra water present in the subsurface between these two reflections.

By performing a two-dimensional migration, we were correcting the influences introduced by the radiation patterns of the GPR signal; however, these radiation patterns are not restricted to the line along which the migration was performed. The signal is also influenced by off-line effects; however, the processed data shown here clearly indicated that reflections were delayed primarily within the infiltration area. True three-dimensional migration would potentially further improve the analysis (Grasmueck et al., 2005).

It has been documented that BB dye is subject to retardation (Ketelsen and Meyer-Windel, 1999; Kasteel et al., 2002) and thus increased moisture content is expected farther into the subsurface than what was outlined by the tracer. Simulations of water and tracer movement in the subsurface using the HYDRUS-1D model (Šimůnek et al., 2008) and specifying an appropriate retardation coefficient showed that the outlined increase in moisture content to approximately the 4-m depth as well as a tracer migration depth of about 2 m is achievable for a sandy soil and for a high value of saturated hydraulic conductivity (500 cm/d).

Dye staining was clearly visible in the excavations for the top 2 m of sediment (Fig. 4 and 5), but the infiltrated water did not have significant influence on the GPR data for this part of the subsurface, neither as attenuation in the dye-stained area nor as scattering effects, which would be expected based on the GPR forward modeling (Fig. 2 and 3). The reason for this discrepancy between expected and actual GPR signals is that most of the infiltrated water was no longer present in the dye-stained areas, as the moisture content samples also showed. Apparently, the infiltrating water did not create sharp transitions between areas of high and low moisture content, which further diminished the influence on reflection GPR data. We did find several interesting differences, however, between the pre- and post-infiltration data sets. Reflection delay effectively illustrated the changes in moisture content at depths to approximately 5 m, and amplitude changes...
The infiltration experiment performed in this study did not represent naturally occurring conditions in Denmark because it is highly unlikely that a rain shower would produce 100 mm of precipitation within 2 h (annual precipitation is 781 mm [Danish Meteorological Institute, 2009]). The purpose of this experiment, however, was not to simulate natural conditions but rather to assess whether useful information regarding unsaturated flow can be obtained using reflection GPR surveys. In future investigations of the type presented here, it could be of interest to apply lower infiltration rates and conduct the infiltration for a longer period without removing the topsoil to better mimic natural conditions. The number of GPR surveys should be increased accordingly to follow the temporal development of the moisture profiles. Also, it would be interesting to see the effect of the BB dye staining on the data by conducting a similar experiment without the tracer, thus removing the effect of the increased conductivity of the applied water, as well as the unknown effect of the viscosity and density of the BB solution.

The experiment performed at Hjelm Heath is in some ways similar to the work presented by Truss et al. (2007), who used time-lapse GPR to monitor natural infiltration; however, they did not assess the infiltration patterns on smaller scale using tracers. The preferential flow observed in the excavation at Hjelm Heath was mostly controlled by macropores and soil heterogeneities. The GPR reflection amplitude analysis and the delay assessment suggest that funneling due to sloping layers was mostly responsible for the generation of preferential flow. The dye tracer patterns found at Hjelm Heath are similar to the findings of Kung (1990), whose field experiment was performed in a comparable environment. Because Hjelm Heath represents soil and subsurface conditions found many places in western Denmark, the obtained results have a broad applicability.

Conclusions

The BB staining revealed that at this field site the unsaturated flow regime is controlled by unstable wetting fronts as well as bypass flow, fingering, and lateral flow. High-resolution reflection GPR was found to be a suitable nondestructive method for mapping complex flow phenomena in the unsaturated zone. The quasi-three-dimensional GPR data set provided an excellent means of assessing both reflection delays caused by electromagnetic velocity changes as well as amplitude differences caused by large-scale movement of water. These results provided more knowledge of the flow regime at the field site. The observed effects were mainly confined to the infiltration area, with GPR data from outside being less or not affected at all.

The changes in GPR signal turned out not to be as significant as expected based on the numerical modeling as well as other experiments described in the literature. We did not manage to resolve the small infiltration patterns outlined by the dye tracer using reflection GPR. Brilliant Blue dye staining is helpful for illustrating and highlighting the existing flow paths; however, due to retardation of the dye, it does not shed light on the deep unsaturated flow. With high-resolution GPR it was possible to map the deeper infiltration, which in this case was substantial, with water percolating much deeper than revealed by the dye staining. The method can also be used in time-lapse measurements of soil moisture development, which will allow for even more detailed assessments of the nature of unsaturated flow.

References


